Fundamentals of Radiation Damage

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ATR NSUF Summer School

Fuels and Materials Course

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MichiganEngineering

The primary objective of this tutorial is to explain the origin of radiation damage and explore some of the results (effects)

Outline

- **Motivation**
- **The Radiation Damage Event**
- **Physical Effects of Radiation**
- **Mechanical Effects of Radiation**

What should you expect to take away from this lecture?

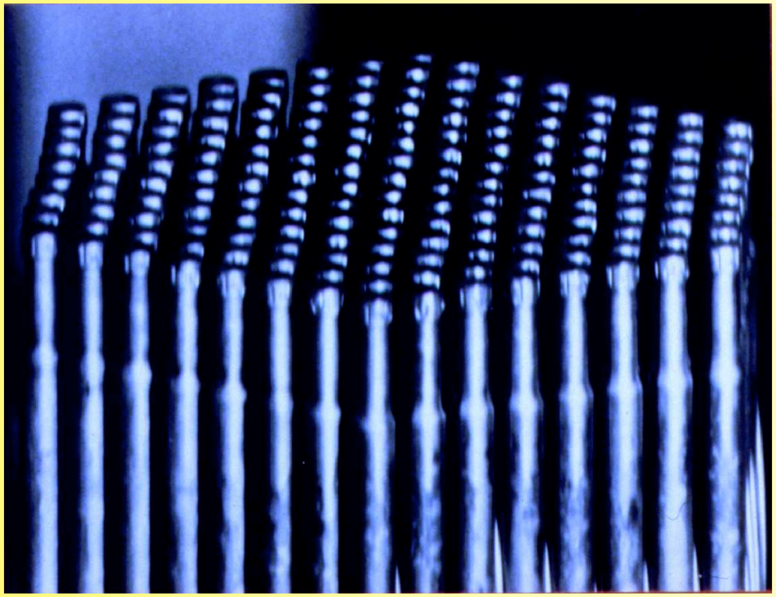
- Basic understanding of neutron interactions with crystalline materials
- How radiation affects the physical properties of materials
- Mechanical and environmental effects of irradiation

Fundamentals of Radiation Damage

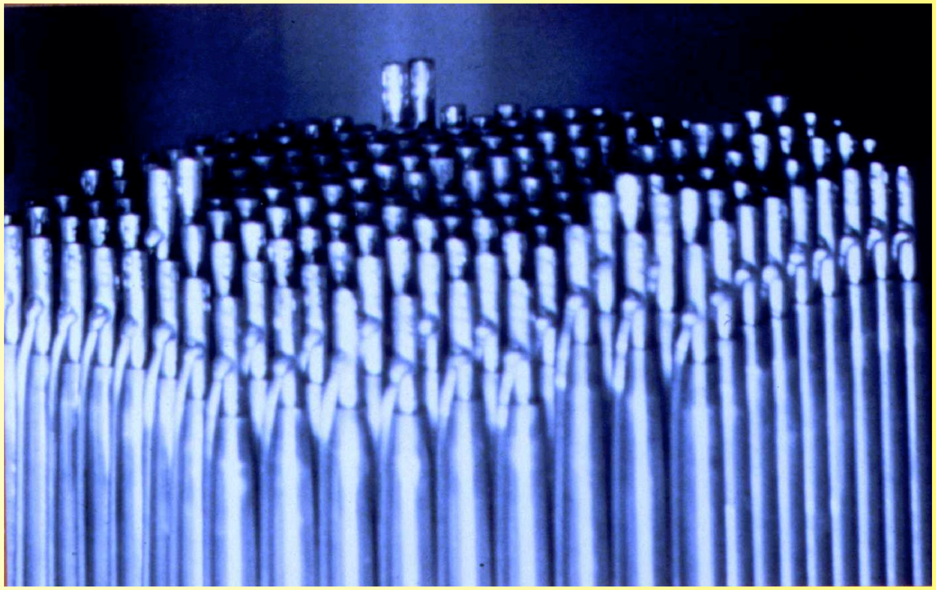
Why do we care about radiation damage?

Swelling

FFTF Fuel Pin Bundles



HT-9, no swelling



316-Ti stainless, swelling

Source: F. Garner

Swelling (con't)

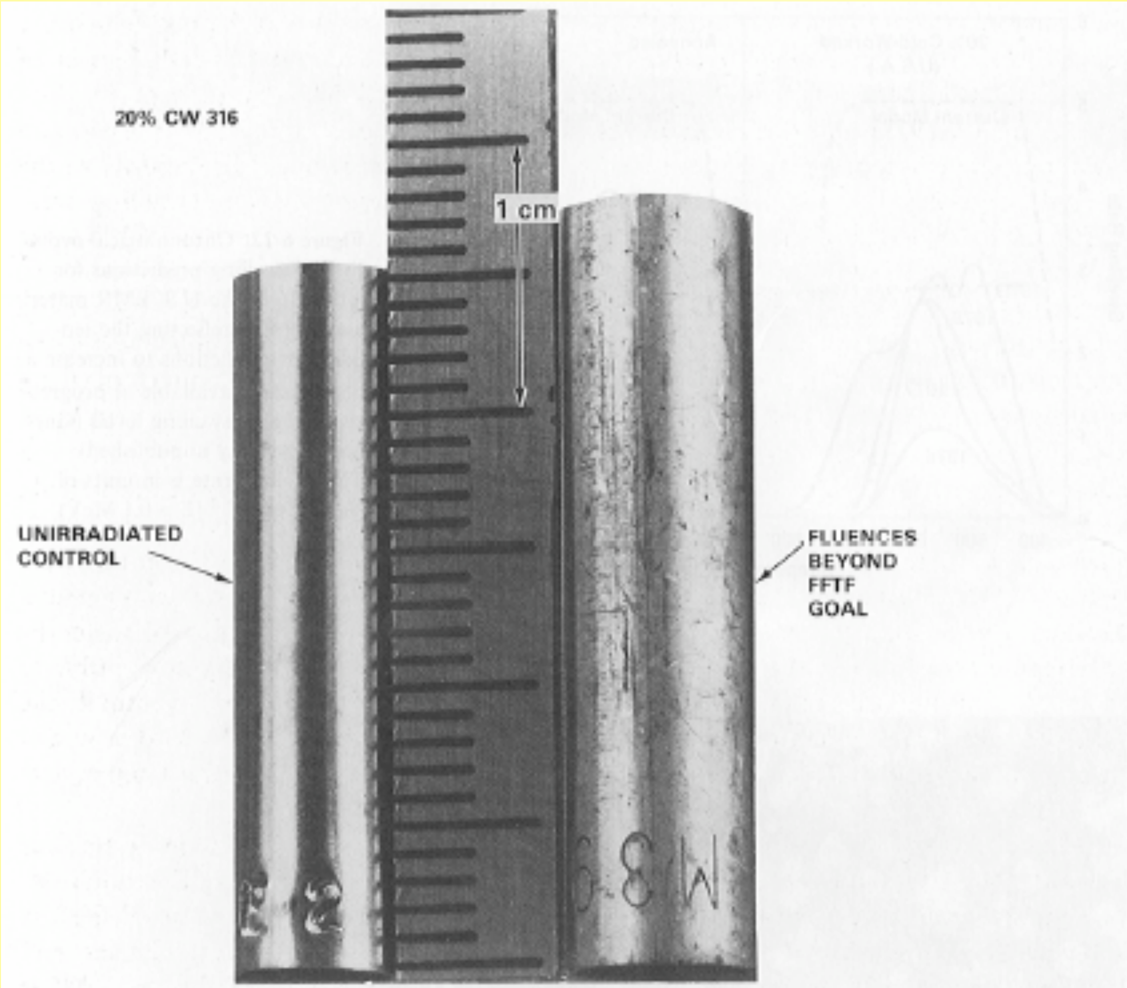
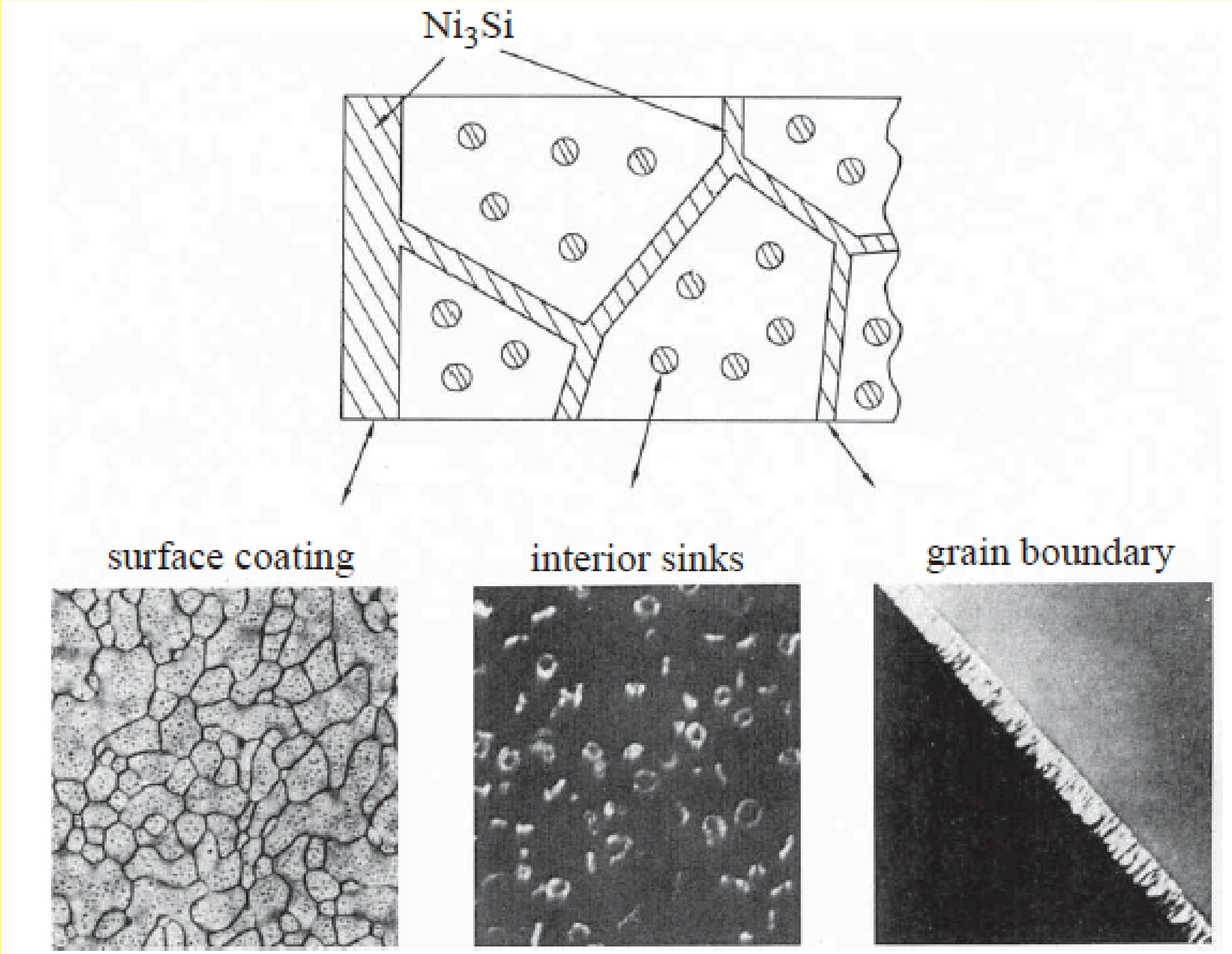


Figure 6-24. Easily observed swelling ($\approx$10% linear, $\approx$33% volumetric) in unfueled 20% cold worked AISI 316 cladding tube at 1.5×10^{23} n cm^{-2} ($E > 0.1$ MeV) or $\approx$75 dpa at 510°C in EBR-II (after Straalsund et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

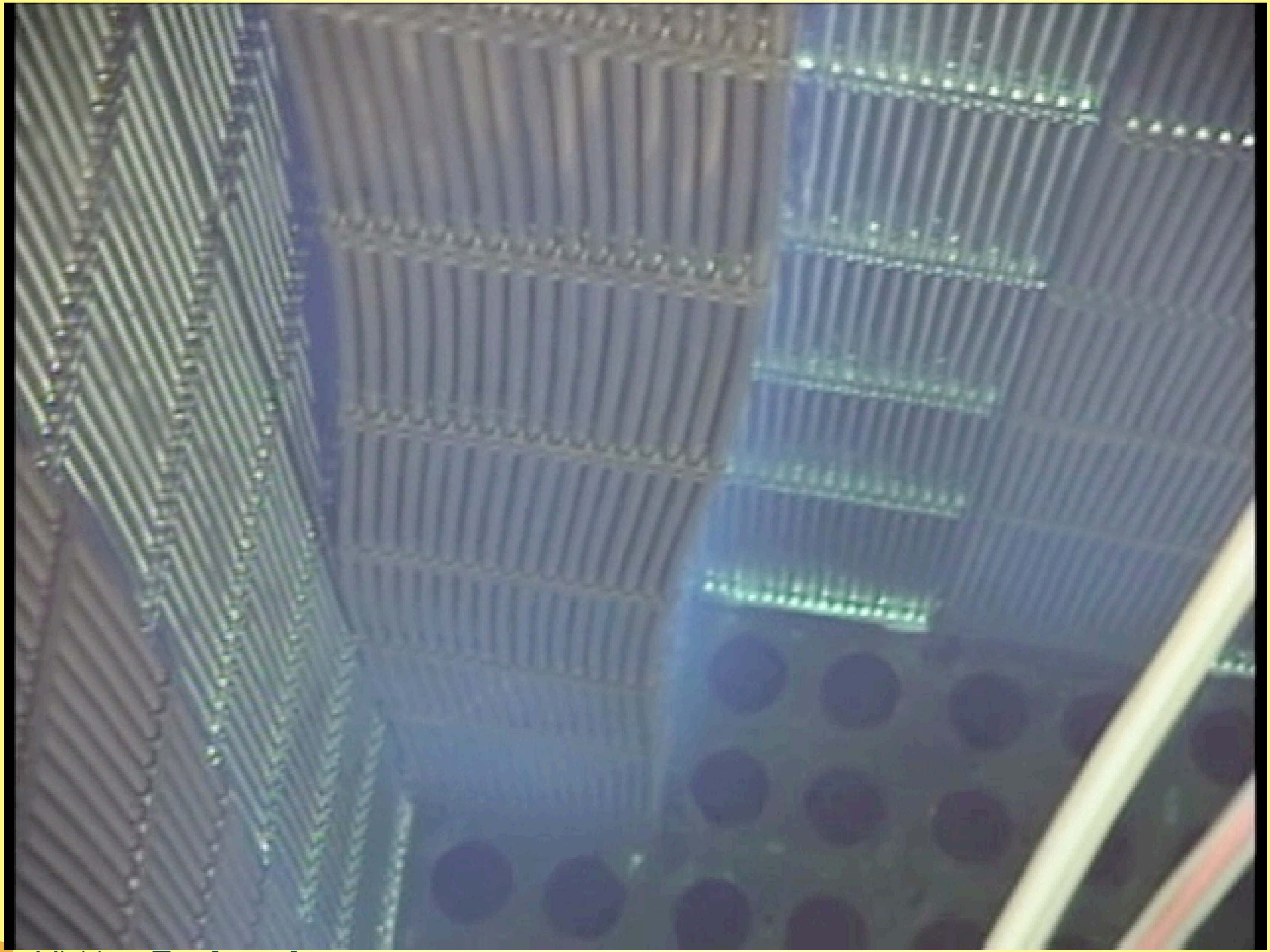
Straalsund et al. 1982

Radiation-induced segregation and precipitation



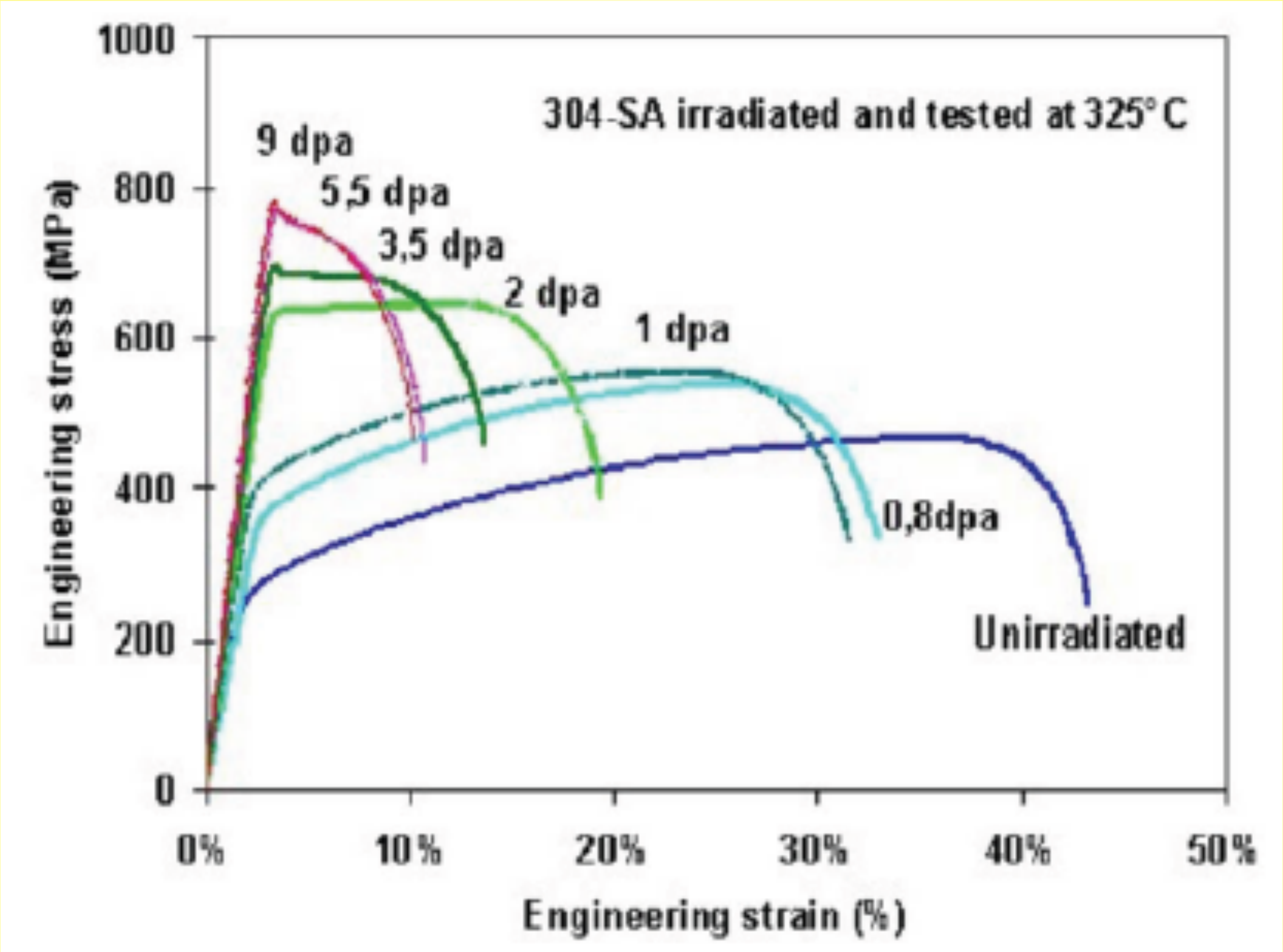
L. E. Rehn, Elsevier Science, 1982.

Irradiation Growth



Areva M5 clad fuel assembly

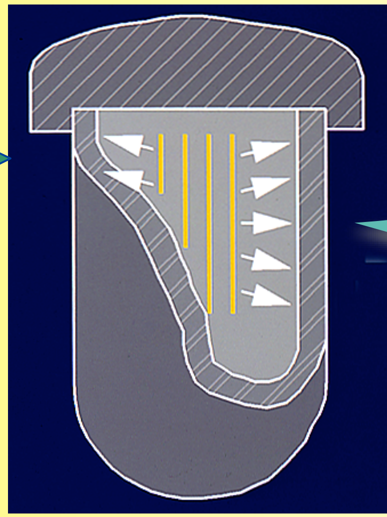
Radiation hardening

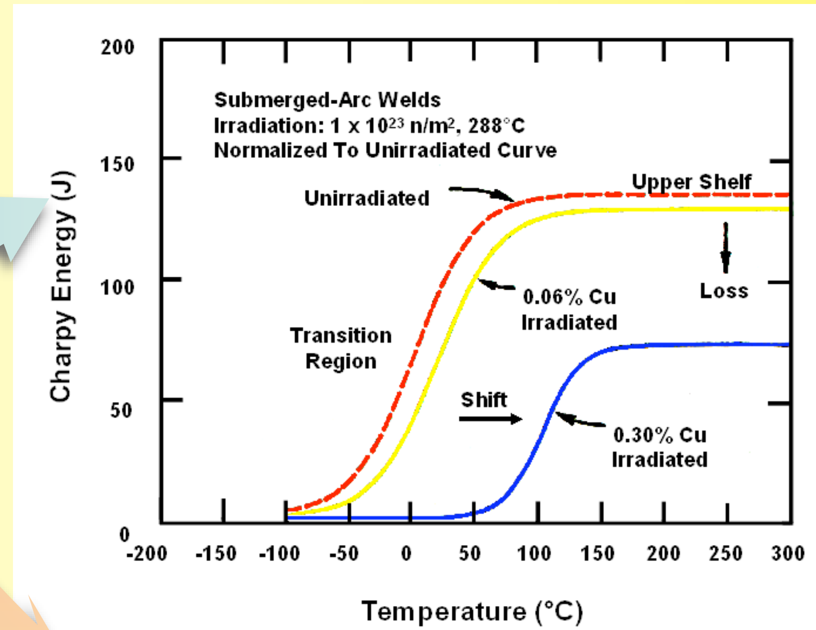


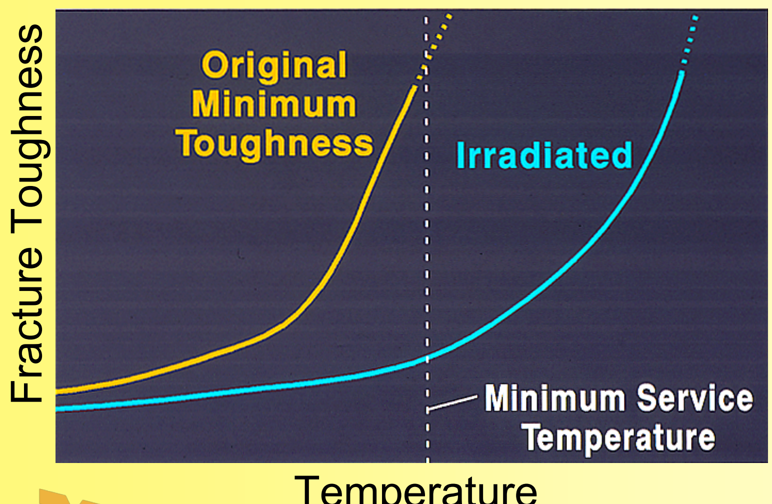
Embrittlement

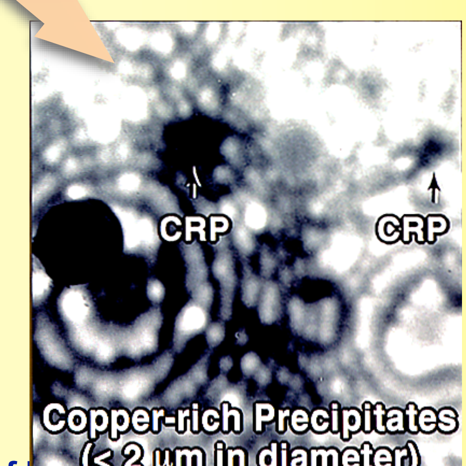
Irradiation Causes Ductile/Brittle Transition Temperature Shift and Upper Shelf Energy Loss — Copper Increases The Effect

Neutron Embrittlement of RPV





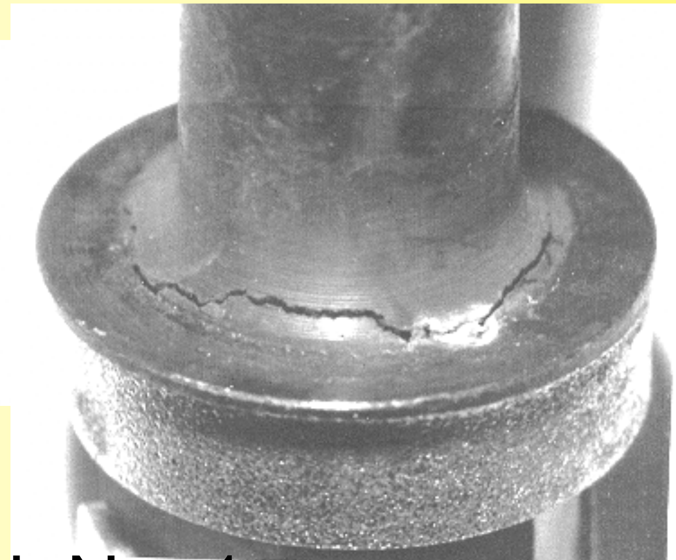


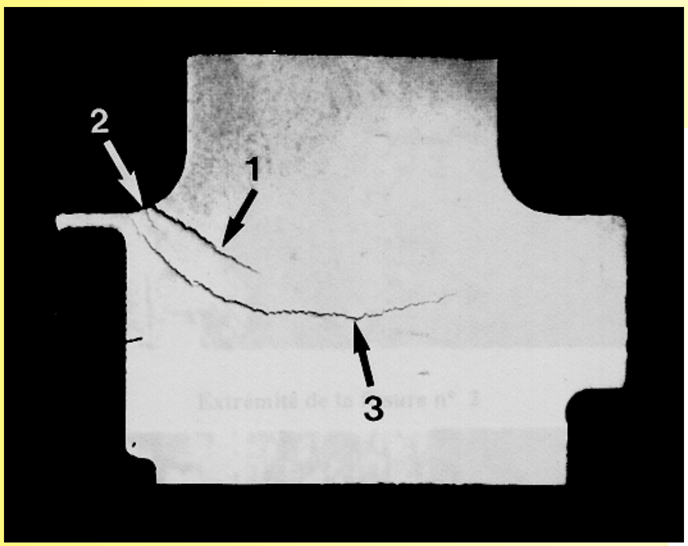


Irradiated Microstructures: Precipitates and Matrix Damage

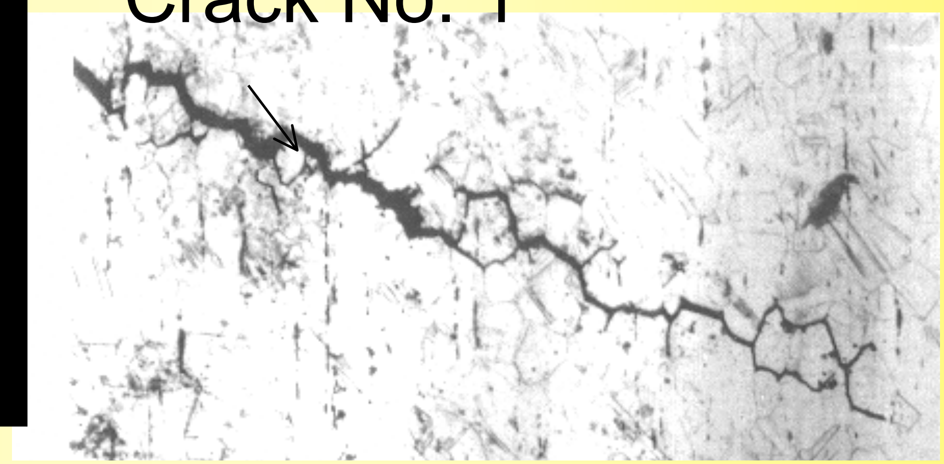
Source: *R. Nanstad*

Irradiation Assisted Stress Corrosion Cracking (IASCC)



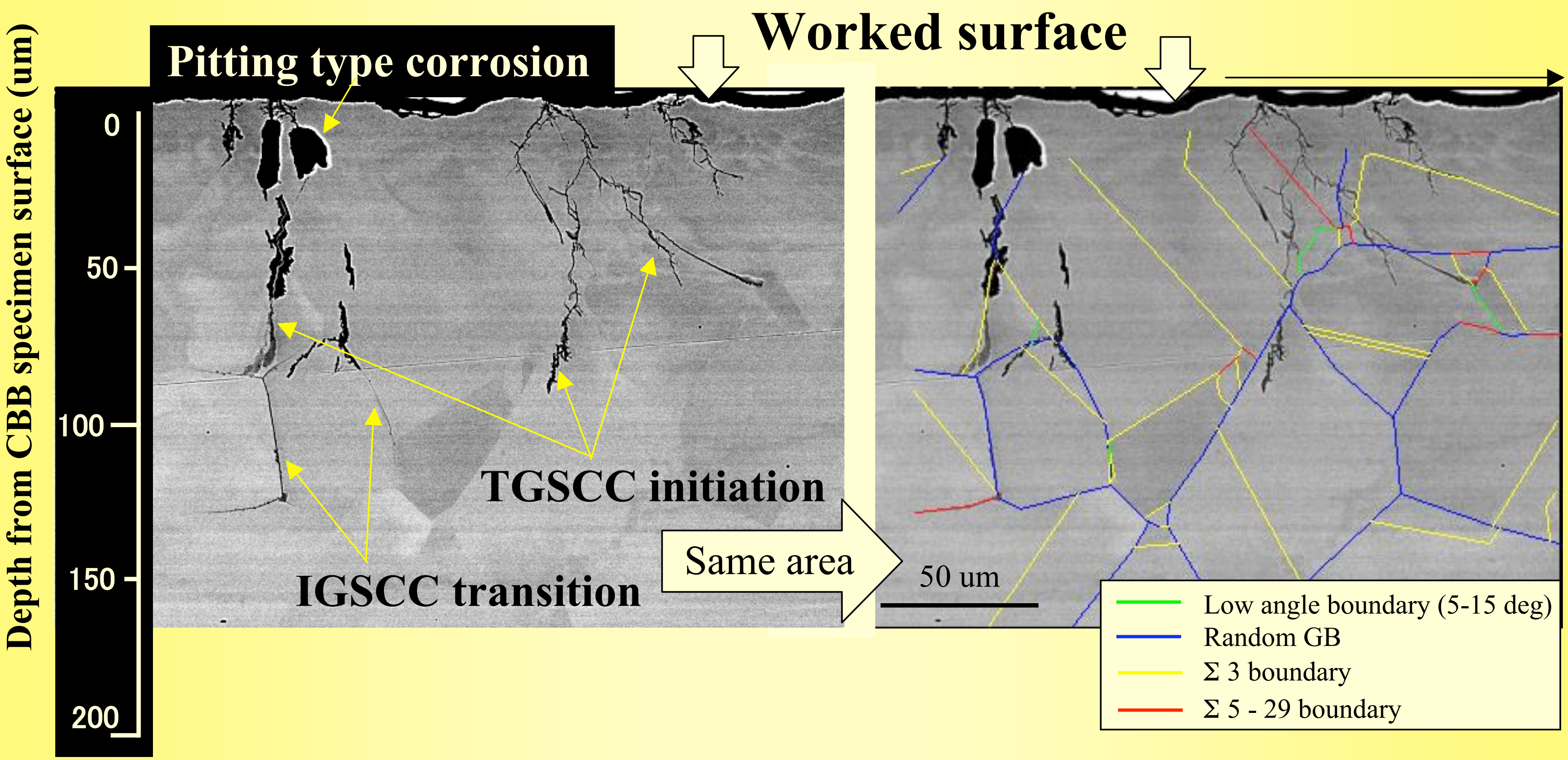


Crack No. 1



Source: P. Scott

IASCC in BWRs



- TGSCC was typically initiated from worked surface and was propagated in deformation area.
- Transition from TGSCC to IGSCC was observed in deeper area.
- Pitting type corrosion was occasionally observed associating with TGSCC.

Fundamentals of Radiation Damage

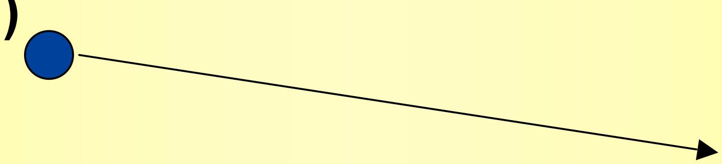
the basics

- **Defect production**
- **Defect concentrations**
- **Defect motion**

Radiation Damage: the basics

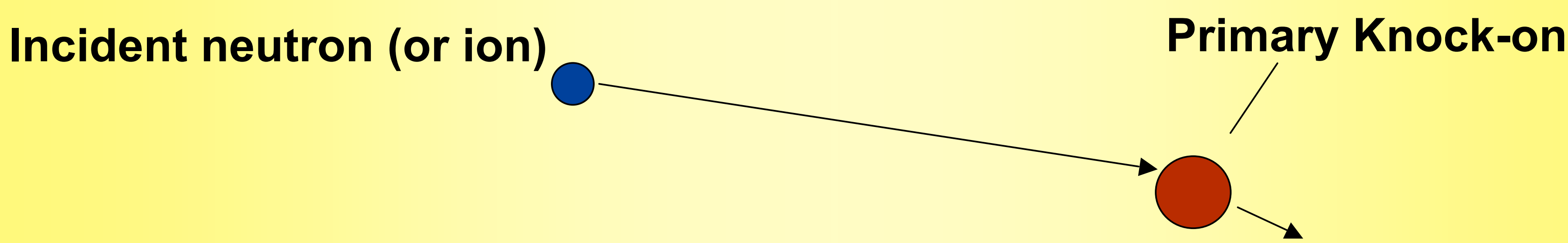
- **All of radiation damage boils down to a common event: collisions between incoming neutrons and atoms in the crystal lattice!**

Incident neutron (or ion)



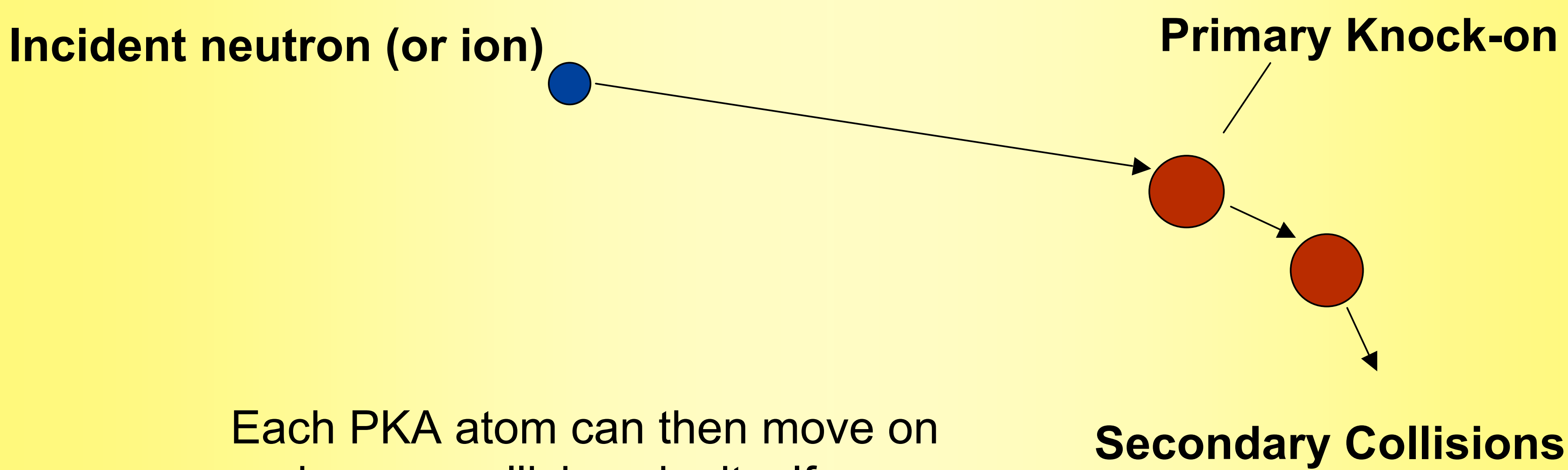
Radiation Damage: the basics

- **All of radiation damage boils down to a common event: collisions between incoming neutrons and atoms in the crystal lattice!**



Radiation Damage: the basics

- **All of radiation damage boils down to a common event: collisions between incoming neutrons and atoms in the crystal lattice!**

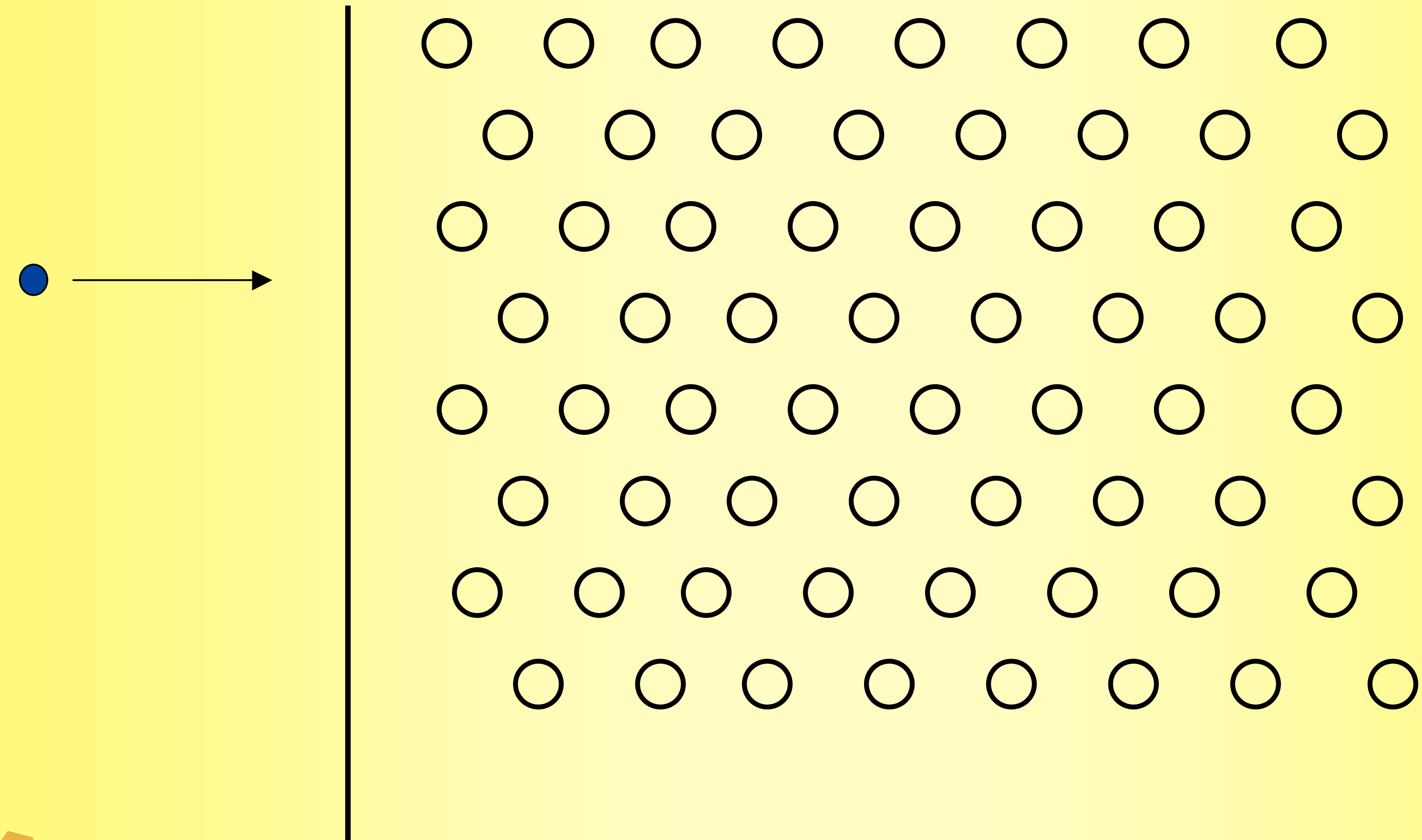


Each PKA atom can then move on and cause collisions by itself.

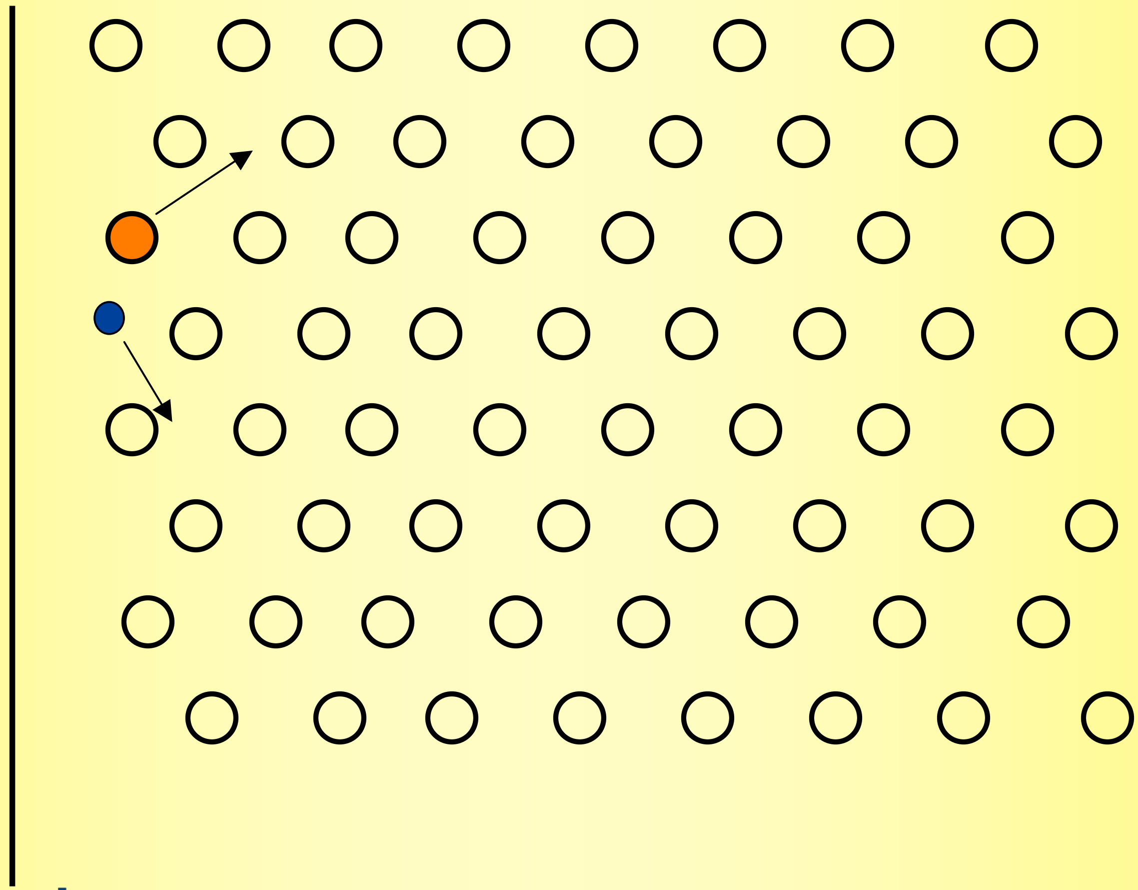
Primary knock-on atoms are an important part of the damage process

- Each neutron/atom collision transfers energy. For neutrons, this number varies
  - Average kinetic energy for PKA in a fission reactor: 10 keV
  - Average kinetic energy for PKA in a fusion reactor: 50 keV
- As long as the energy of the PKA is above the energy to displace an atom (E_d ~ 40 eV), each subsequent KA will transfer energy to other atoms in the crystal.
- This process continues creating a cascade.

Simple Picture

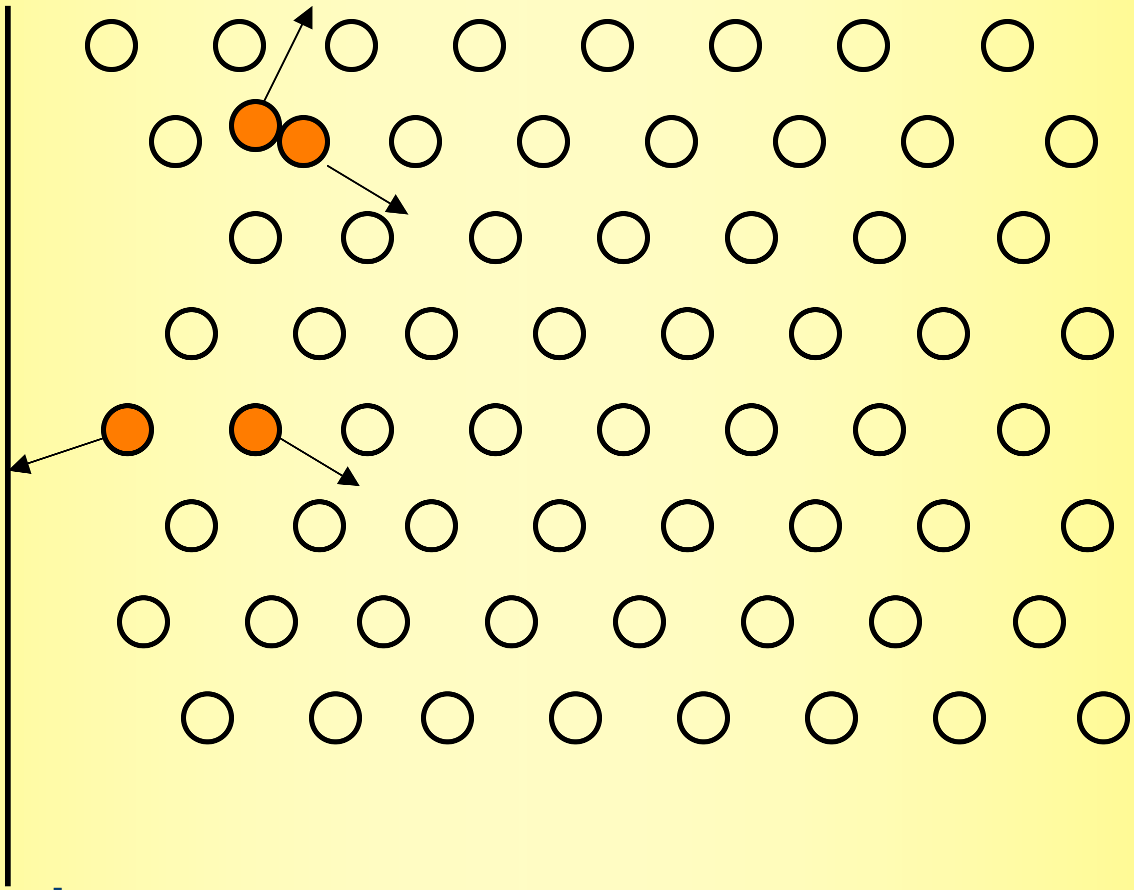


Simple Picture



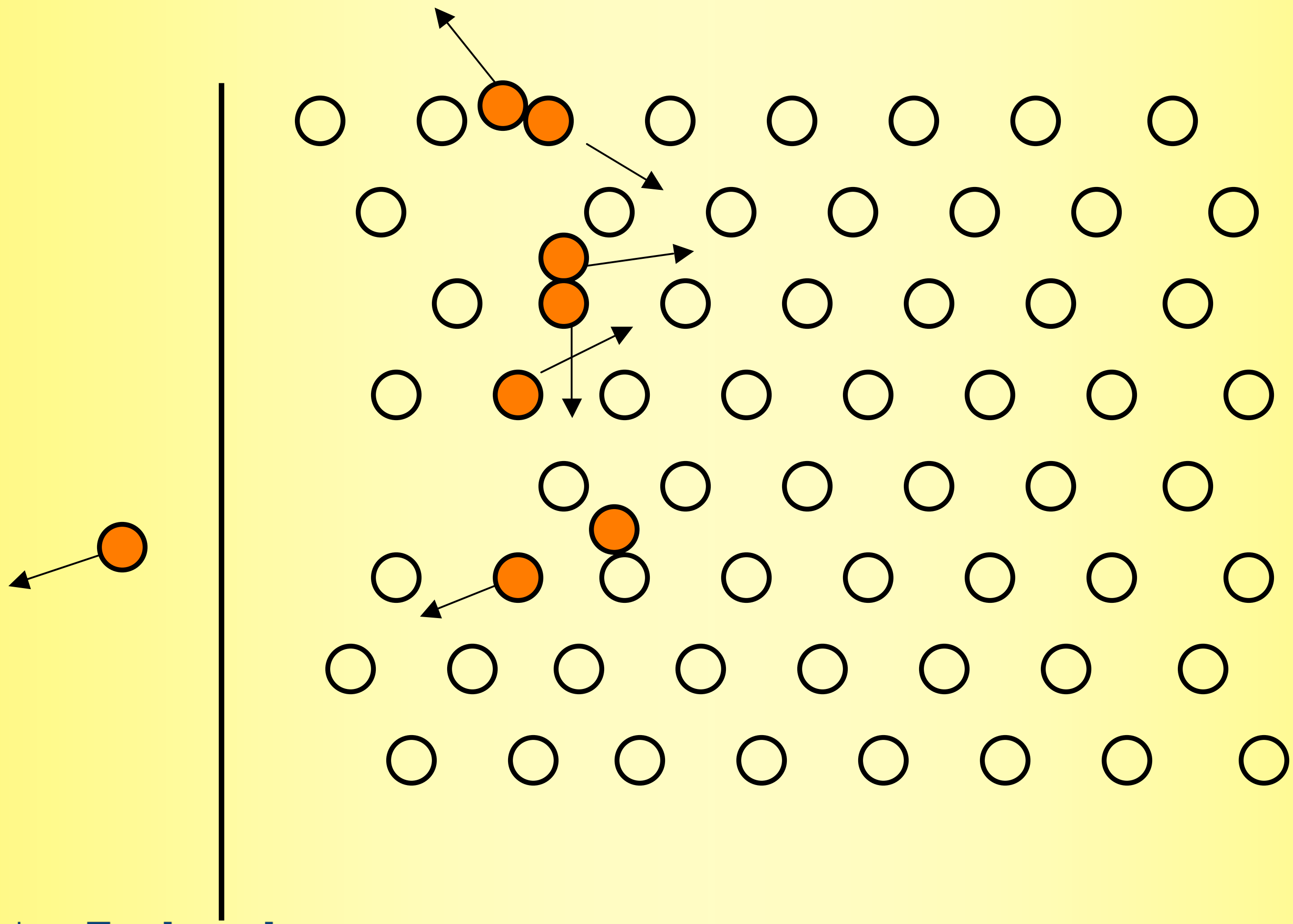
Source: T.R. Allen

Simple Picture



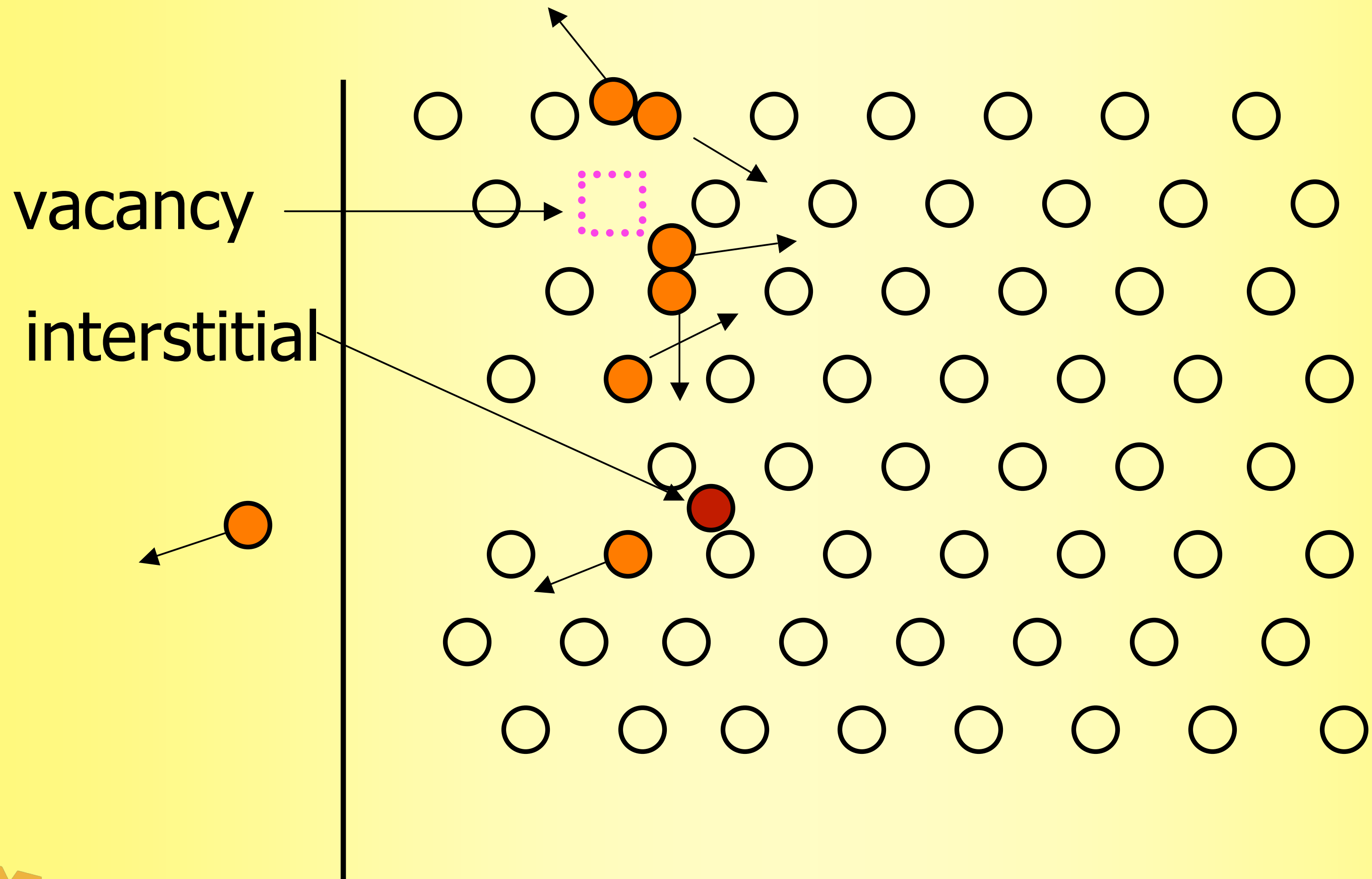
Source: T.R. Allen

Simple Picture

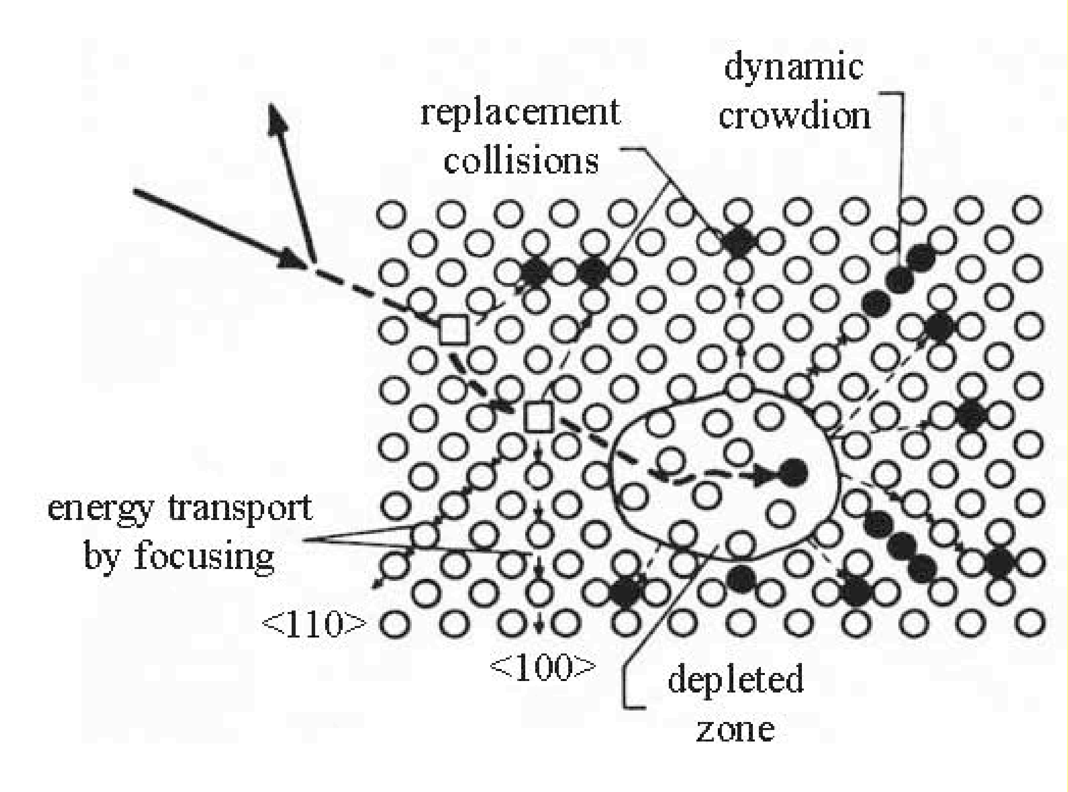


Source: *T.R. Allen*

Simple Picture

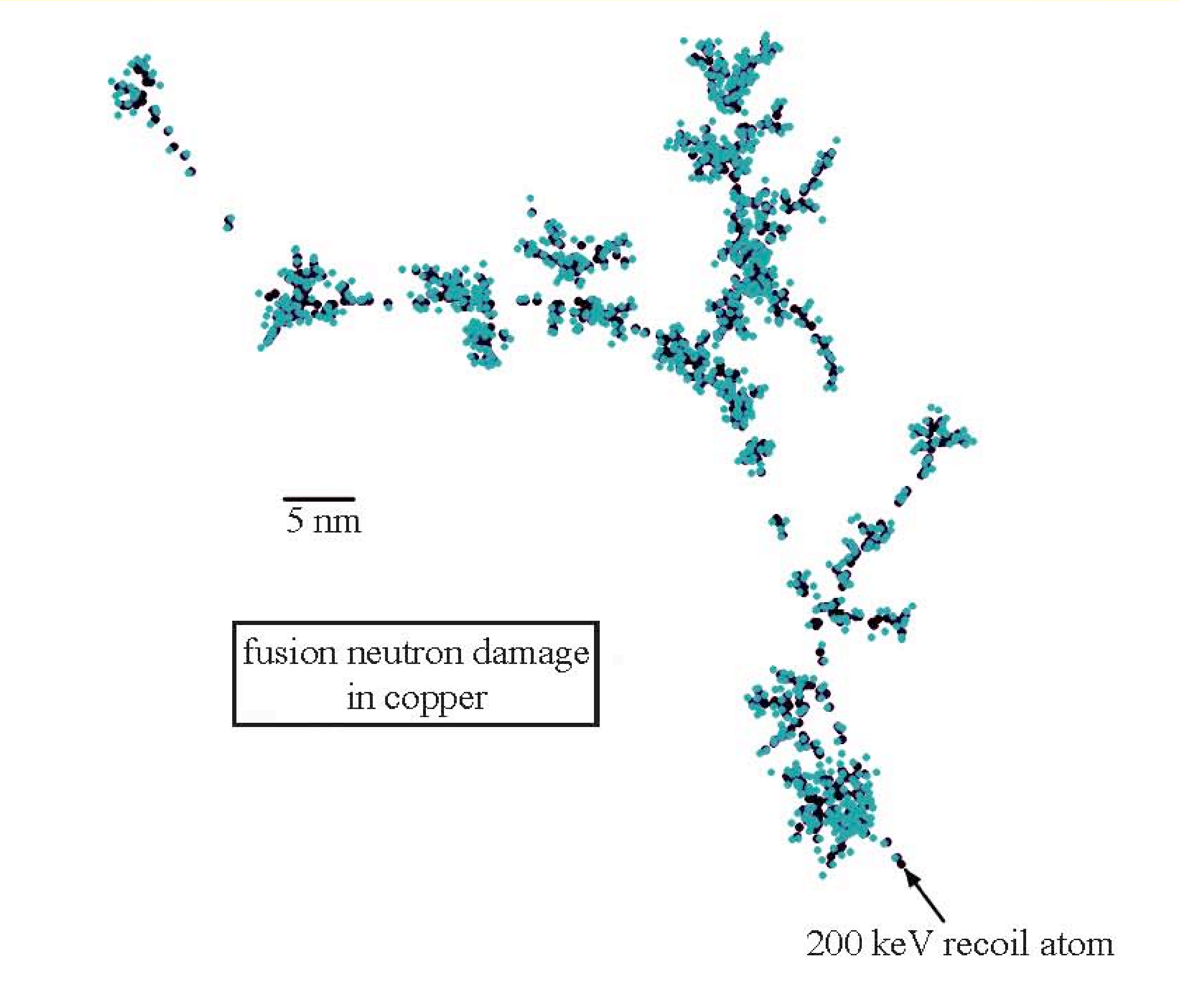


Still a relatively simple picture



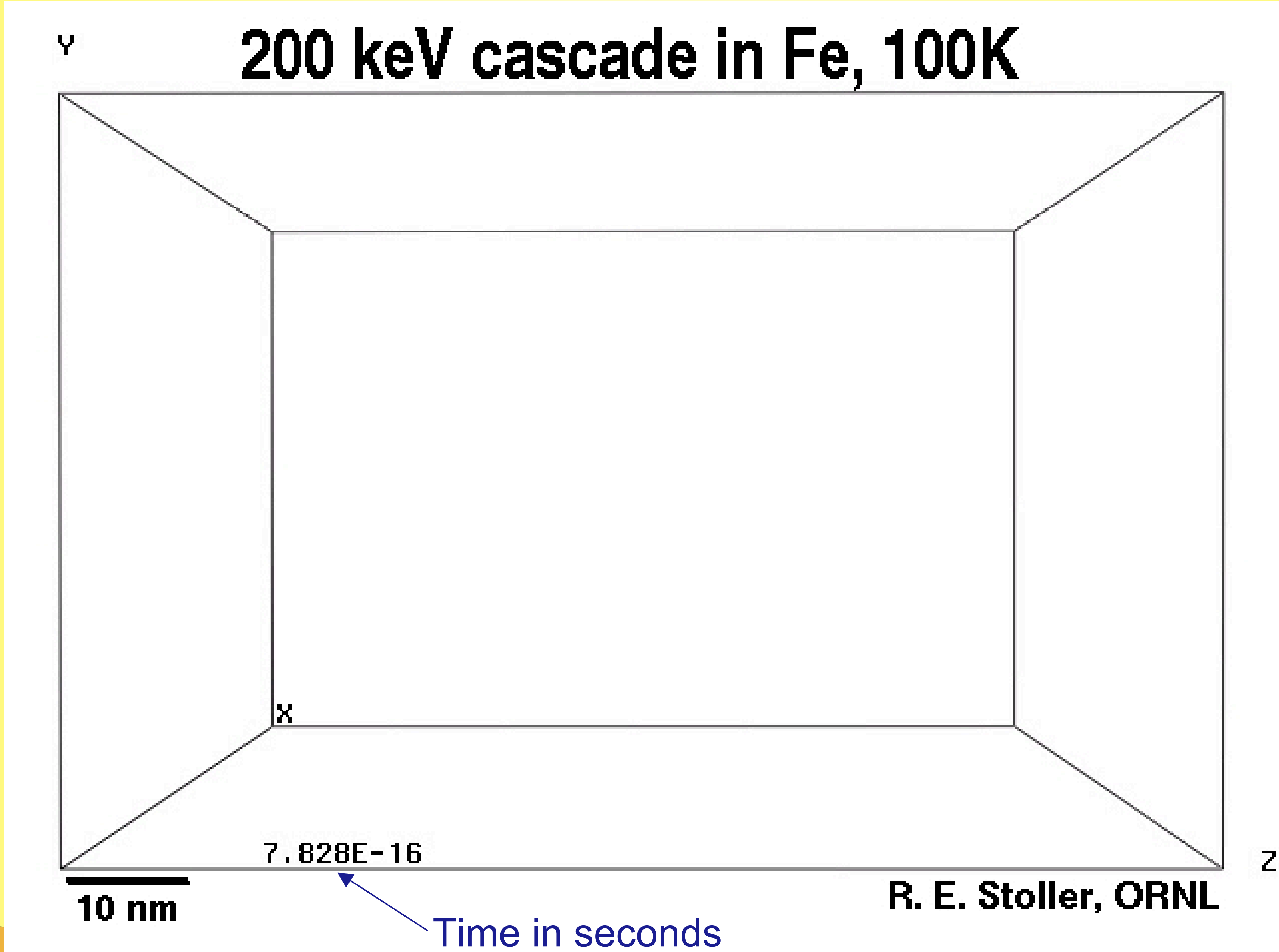
A. Seeger, 1958

A more accurate picture

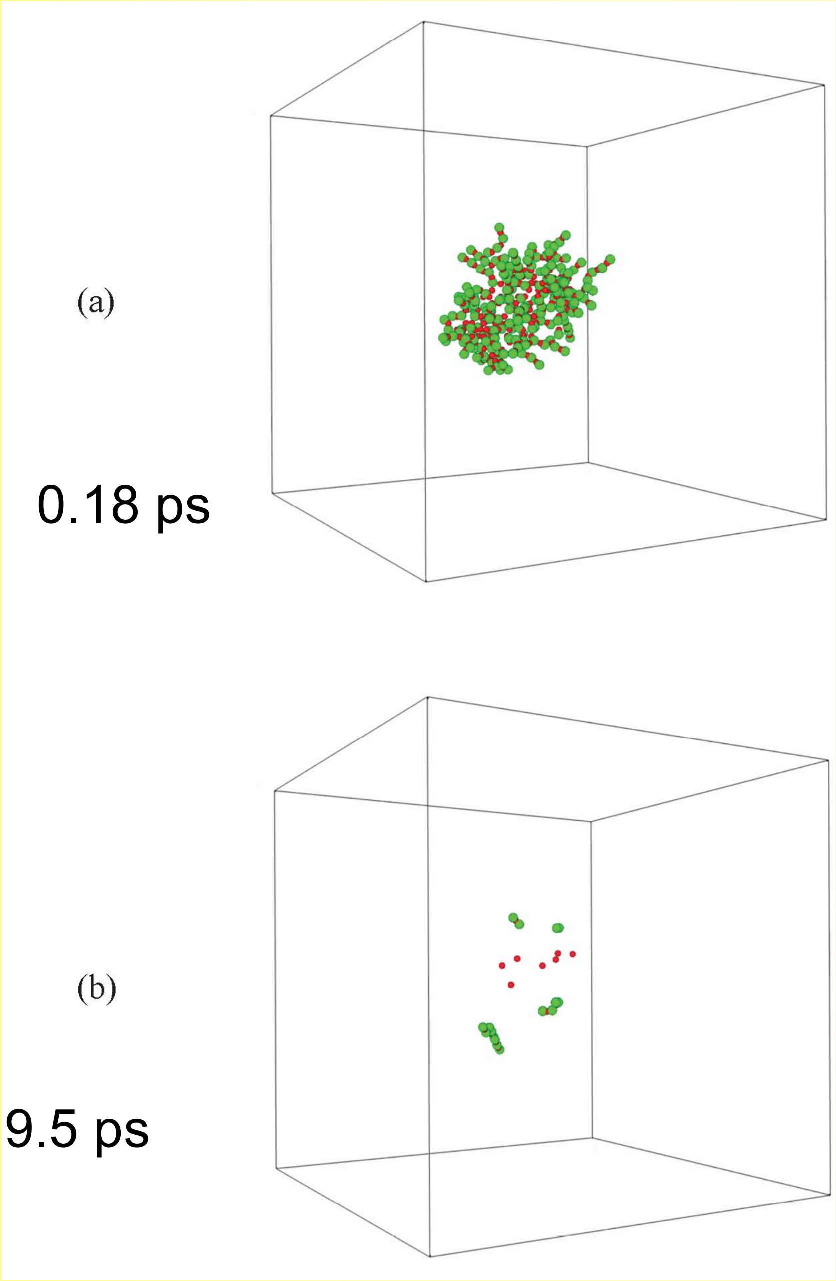


H. Heinisch, J. Metals, 1996

The real thing



MD simulation



1 keV PKA in iron at 100K

R. E. Stoller, J. Metals, 1996

Dynamics of a displacement cascade

- **The creation and subsequent decay of a displacement cascade consists of three overlapping stages.**
  - **Collisional phase ~ 10^{-13} s: All of the collisions associated with the PKA occur.**
  - **Cooling phase ~ 10^{-11} s: Annihilation, in-cascade clustering, replacement events occur.**
  - **Diffusional interactions phase > 10^{-8} s: Mobile defects interact in the lattice to form clusters or annihilate via recombination or at sinks.**
- **The total number of atoms displaced by each neutron depends on a number of factors:**
  - **Incoming particle (energy, direction)**
  - **Material (E_d, crystal structure)**
  - **Temperature**

Radiation defect production timescale

Time (s)	Event	Result
10^{-18}	**Energy transfer from the incident particle**	**Creation of a primary knock-on** **atom (PKA)**
10^{-13}	**Displacement of lattice atoms by the PKA**	**Displacement cascade**
10^{-11}	**Energy dissipation, spontaneous recombination and clustering**	**Stable Frankel pairs** **(single interstitial atoms (SIA) and vacancies) and defect clusters**
> 10^{-8}	**Defect reactions by thermal migration**	**SIA and vacancy recombination, clustering, trapping, defect emission**

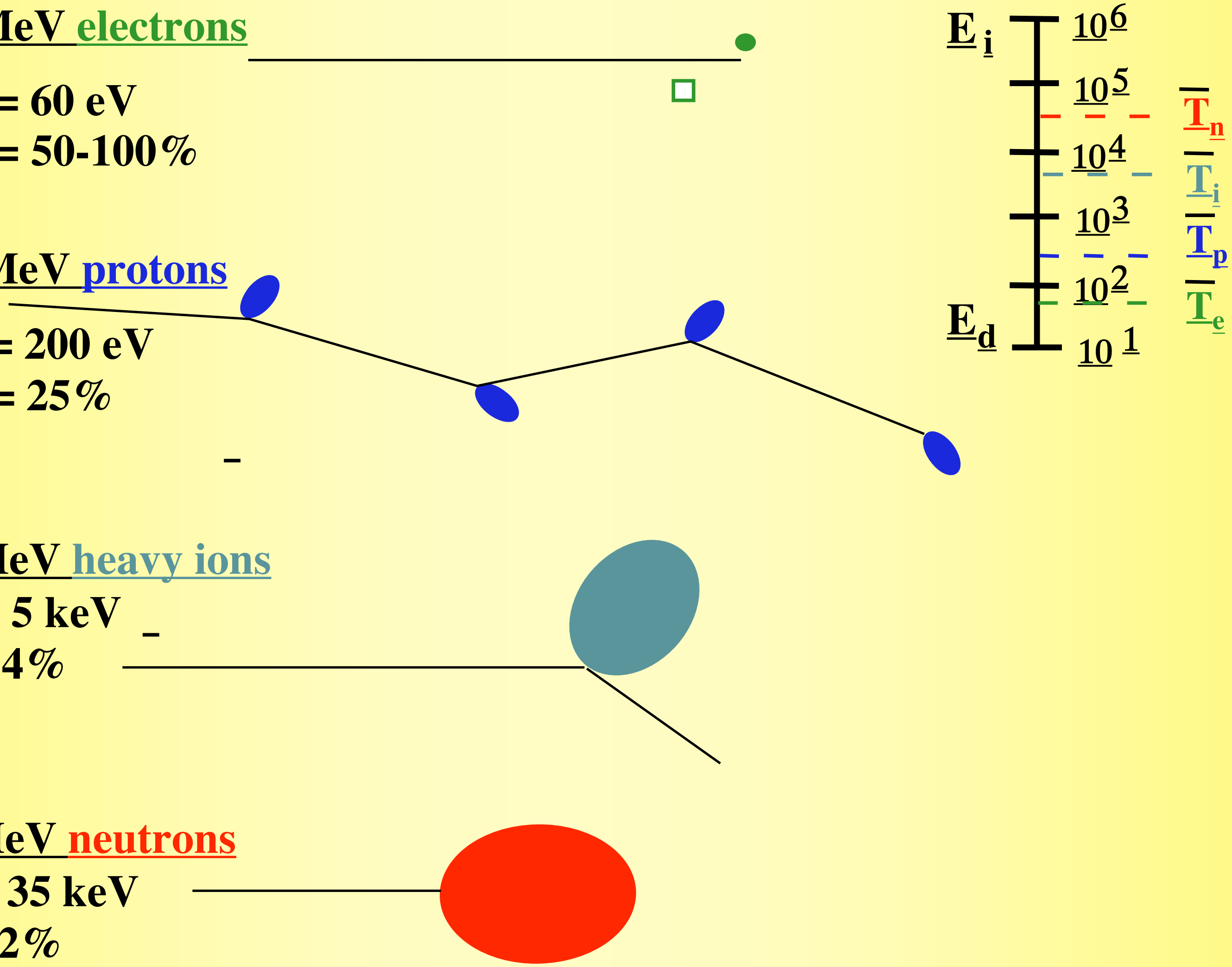
Ions also create cascades and defects

1 MeV electrons
$\bar{T}$ = 60 eV
ε = 50-100%

1 MeV protons
$\bar{T}$ = 200 eV
ε = 25%

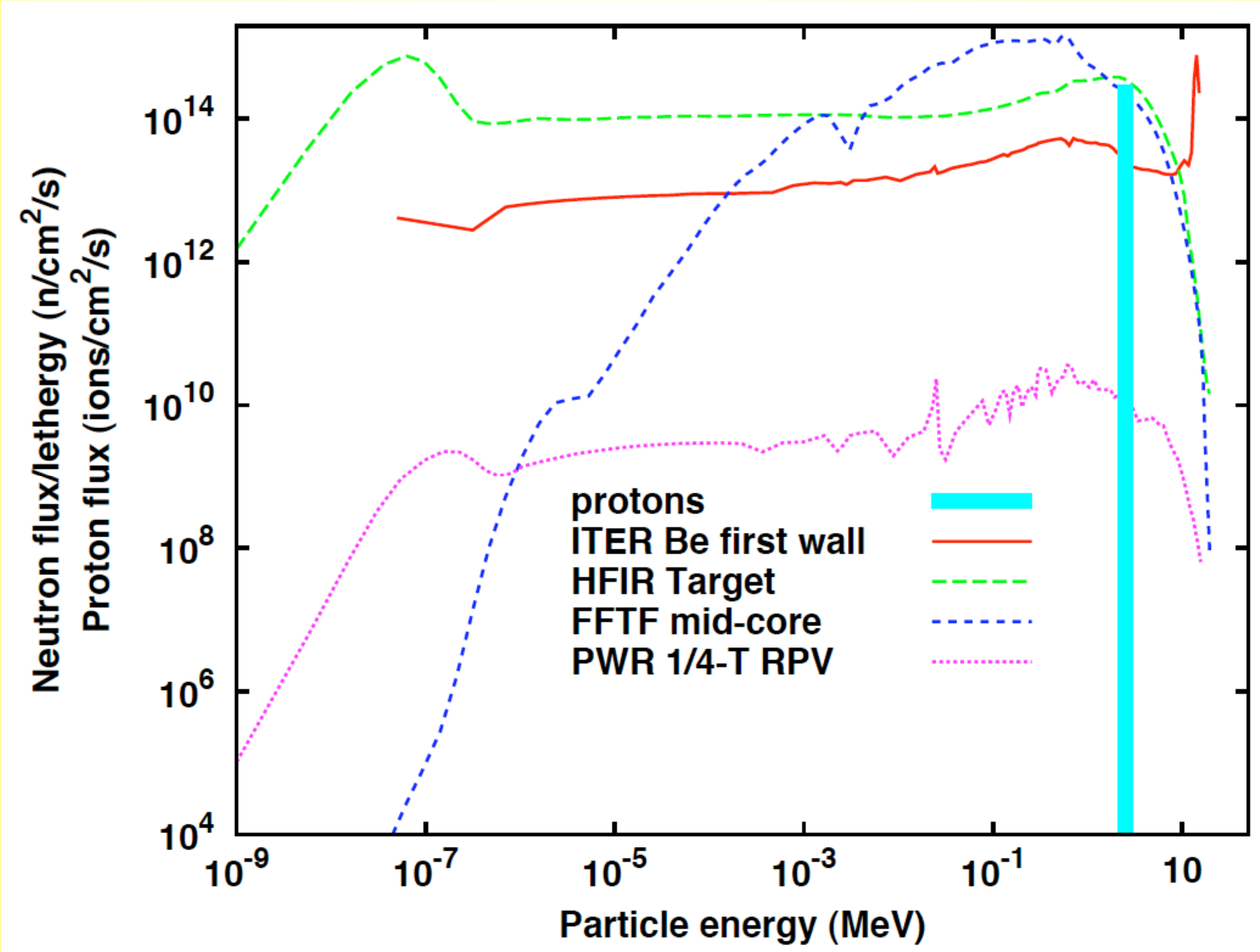
1 MeV heavy ions
$\bar{T}$ = 5 keV
ε = 4%

1 MeV neutrons
$\bar{T}$ = 35 keV
ε = 2%



G. S. Was, Radiation Materials Science, 2007

Energy spectrum of various radiation sources

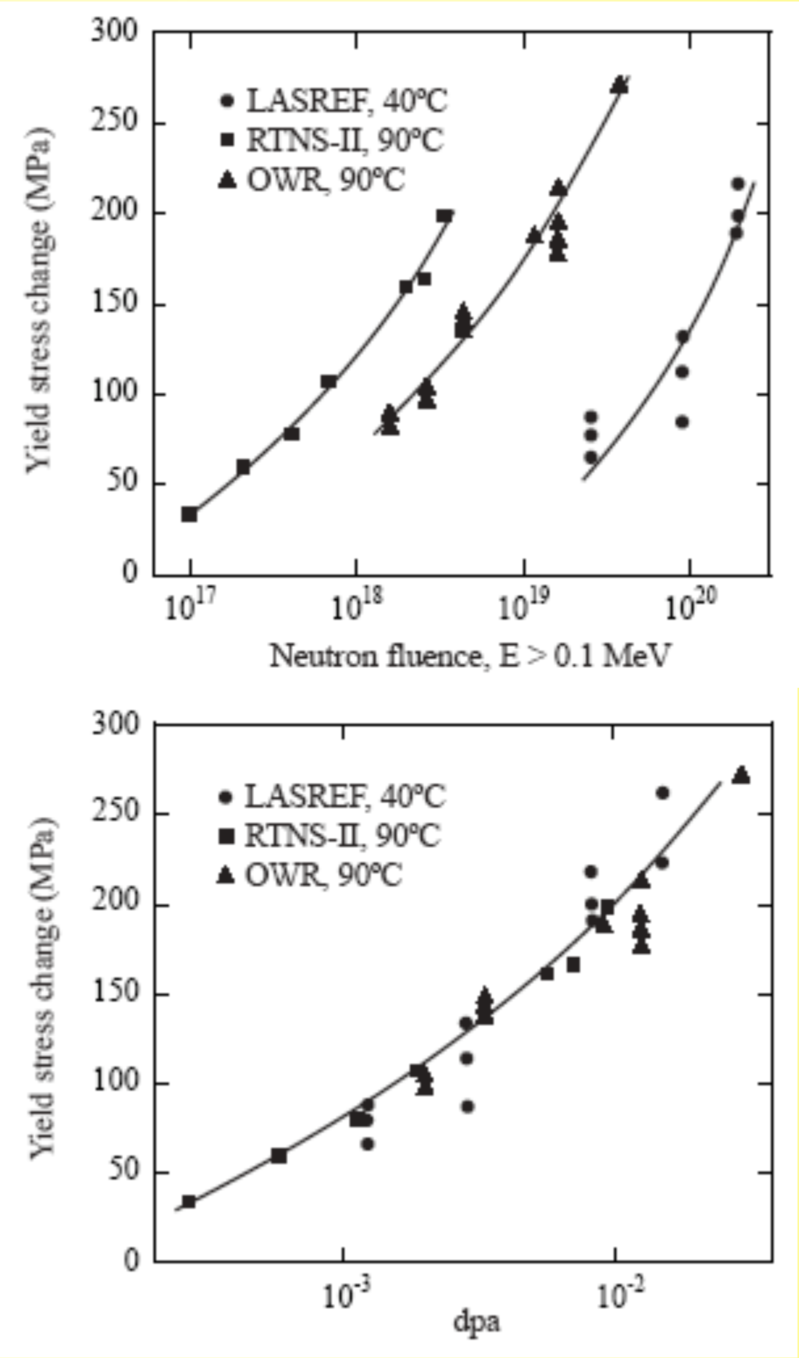


G. S. Was, Radiation Materials Science, 2007

Damage is often normalized into units of "displacements per atom"

- Displacement per atom (dpa) = average number of displacements of each lattice atom
- This calculated value is convenient as it can help normalize between different neutron spectra or even particles
- Rules of thumb:
  - 0.7×10^{21} n/cm^2 (E>1 MeV) ≈ 1 dpa in SS
  - 0.4×10^{21} n/cm^2 (E>1 MeV) ≈ 1 dpa in Zr
- For a fast reactor core (10^{15} n/cm^2/s), displacement rates of 10^{-6} dpa/s may be experienced. Each atom is displaced every ~12 days.

The value of quantifying radiation damage



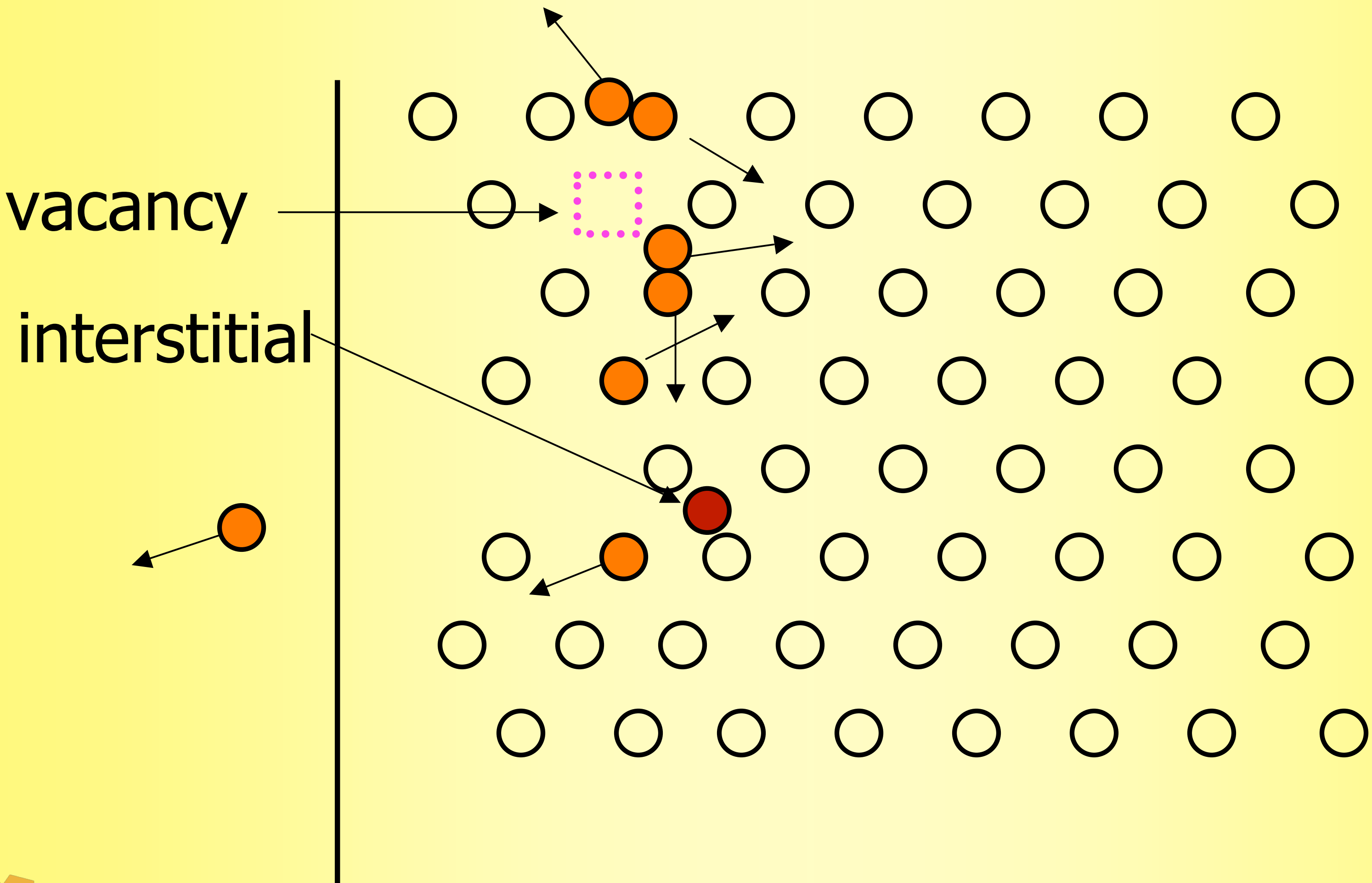
L. R. Greenwood, JNM 1994

Classification of defects

Point	Vacancies, interstitials
Line	dislocation
Area	Stacking fault, grain boundary
Volume	void

Back to the simple picture

Vacancies and interstitials are the primary defects resulting from irradiation



Source: T.R. Allen

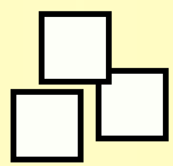
Why are we interested in vacancies and interstitials?

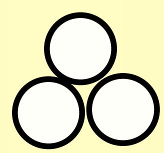
Options for vacancies and interstitials

- they can react with each other (recombination)

□ + ○ = null

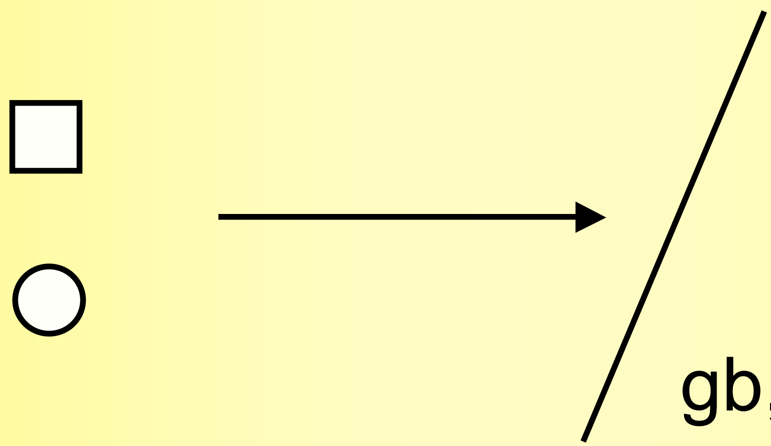
- they can react with themselves (clustering)

□ + □ + □ =  clusters
e.g. dislocation loops

○ + ○ + ○ =  clusters
e.g. voids

Options for vacancies and interstitials

- they can diffuse to sinks (free surfaces, grain
  boundaries
  dislocations,
  precipitate interfaces
  e.g. RIS)



gb, dislocation, ppt, etc.

Radiation induced defects are produced in very large numbers

- Depending on material, temperature, and dose rate, excess vacancies and interstitials can be created at many orders of magnitude above thermal equilibrium.

How many vacancies and interstitials?

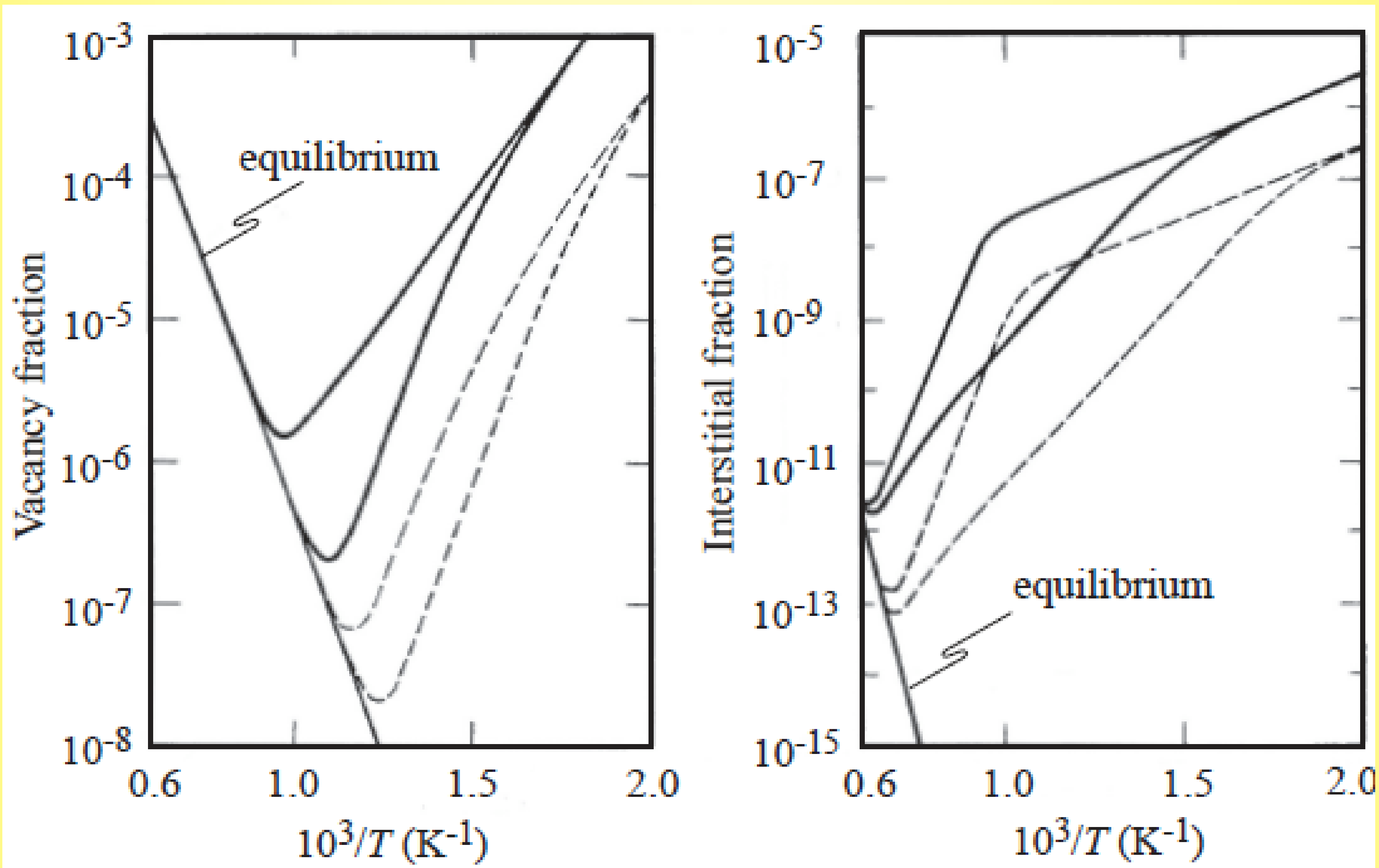
Equilibrium concentration (fraction) of vacancies and interstitials in aluminum at room temperature and 10°C below the melting point.

Room temperature:
$C_v \sim 10^{-11}$
$C_i \sim 10^{-50}$

650°C:
$C_v \sim 10^{-3}$
$C_i \sim 10^{-14}$

How many vacancies and interstitials are produced under irradiation?

$C_v \sim 10^{-6}$ to 10^{-4} $\quad$ $C_i \sim 10^{-12}$ to 10^{-6}



D.R. Olander, 1976

Freely migrating defects and their actions are the key to radiation damage

- Regardless of the nature of radiation (reactor, spectrum, particle), the surviving defects are the key for long-term material changes and properties
- Defects may
  - Recombine
  - Diffuse
  - Cluster
- The latter two possibilities will result in distinct changes.

What about diffusion of vacancies and interstitials

Defect diffusion is described by their diffusion coefficients:

$$D_v, \; D_i$$

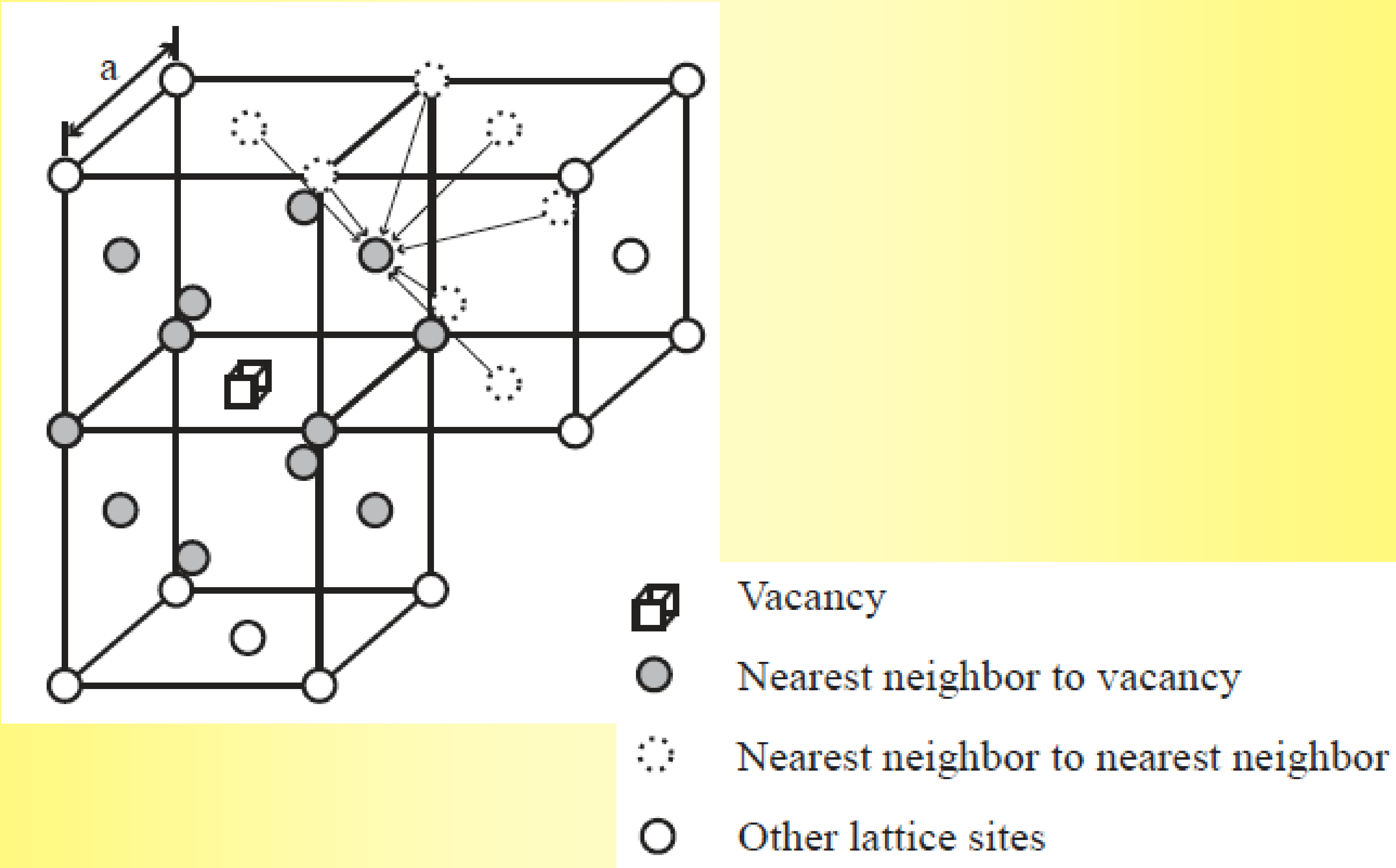
For diffusion of atoms via vacancies and interstitials, we have:

$$D_{atom} = D_v^o \times C_v$$

But $$D_v = D_v^o \times C_{atom}$$

So $$D_v, D_i >> D_{atom} \,!$$

What about diffusion of vacancies and interstitials

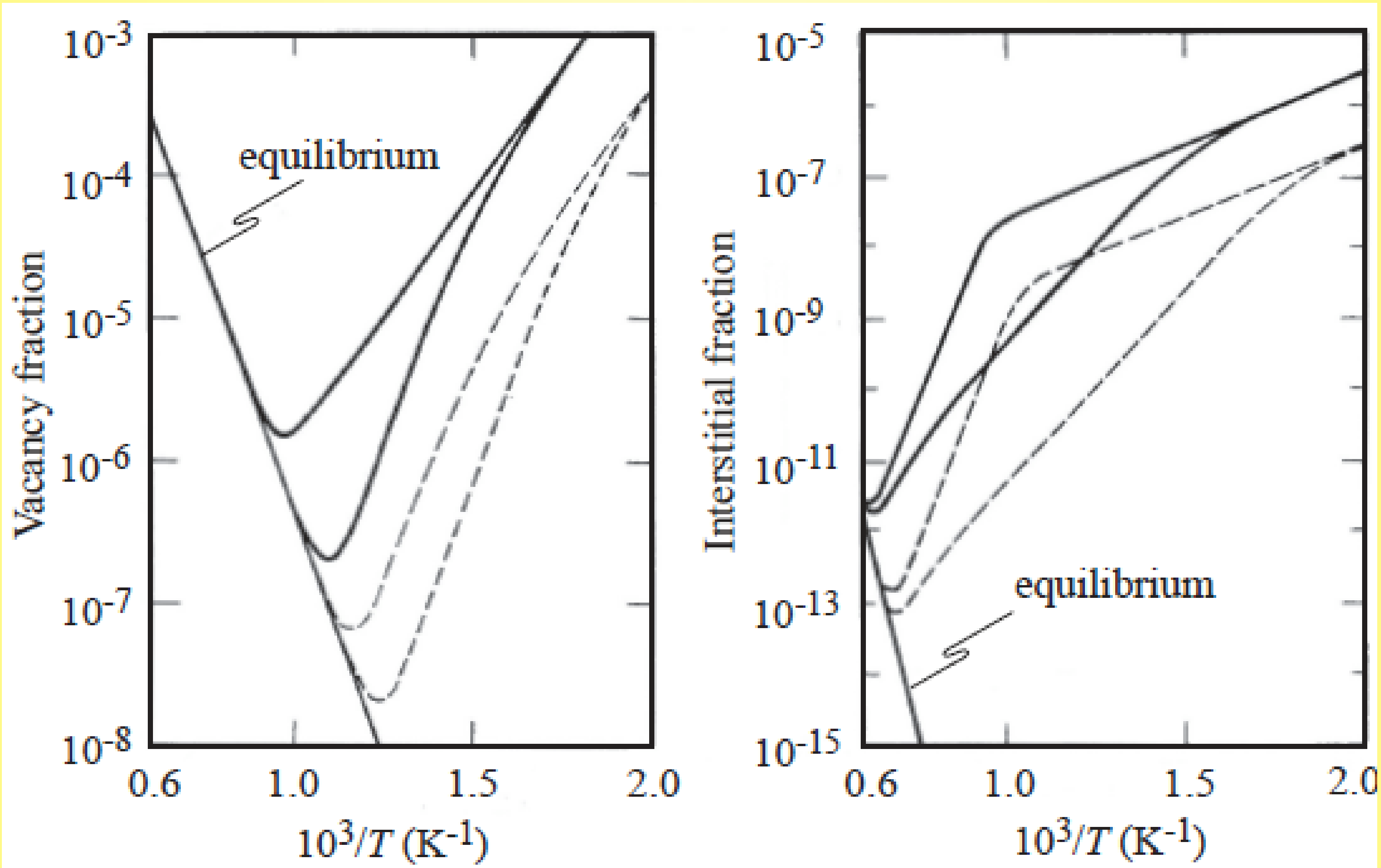


D.R. Olander, 1976

What about diffusion of vacancies and interstitials

D_v, D_i >> D_{atom} because C_v, C_i <<1. That is, atoms need defects to be nearby in order to move, which is much less probable than the case of defects, which need atoms near by to move.

Remember that irradiation greatly increases the number of vacancies and interstitials relative to thermal equilibrium



and $C_v > C_i$

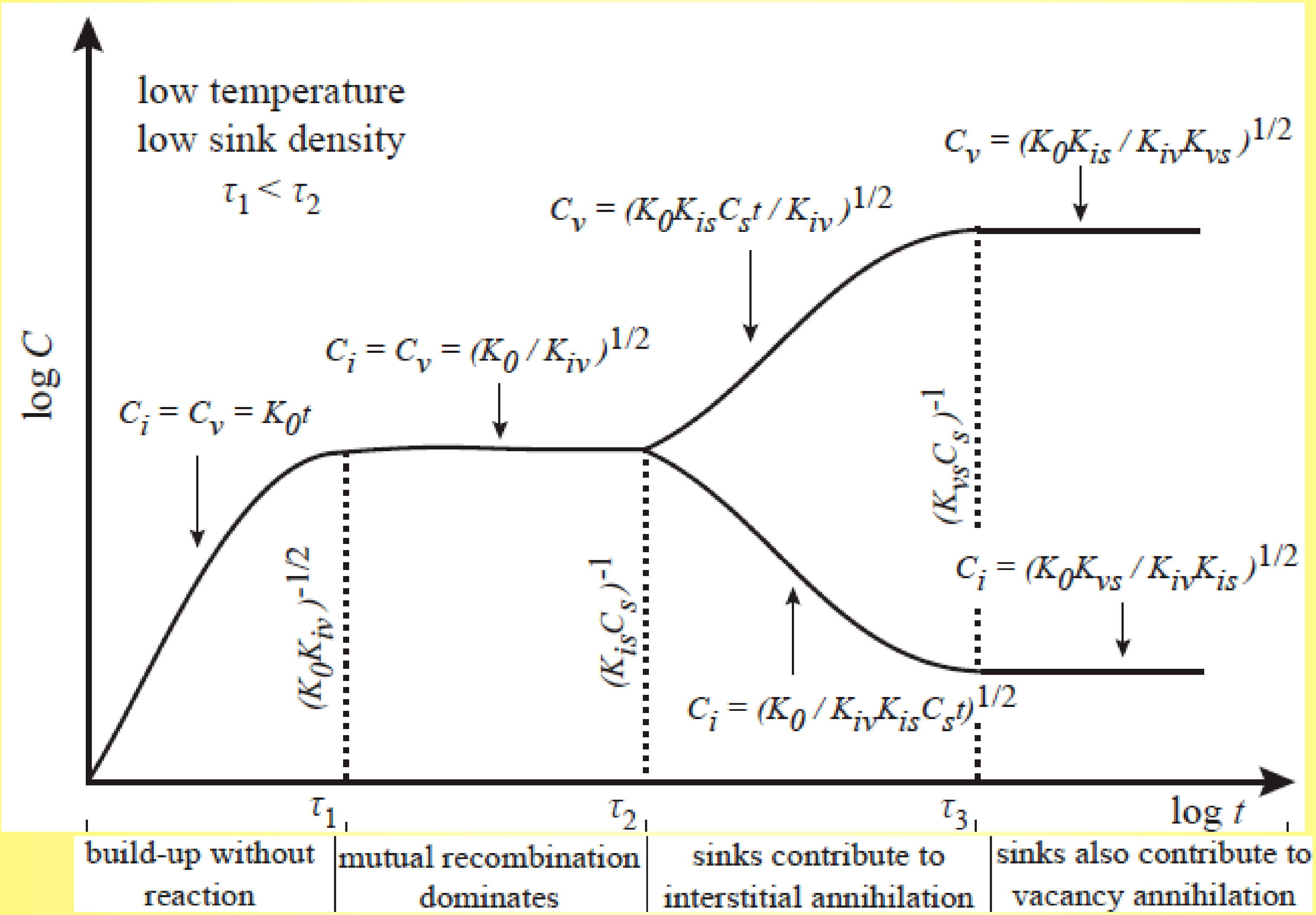
D.R. Olander, 1976

What about diffusion of vacancies and interstitials

So, $D_v < D_i$ and $C_v > C_i$

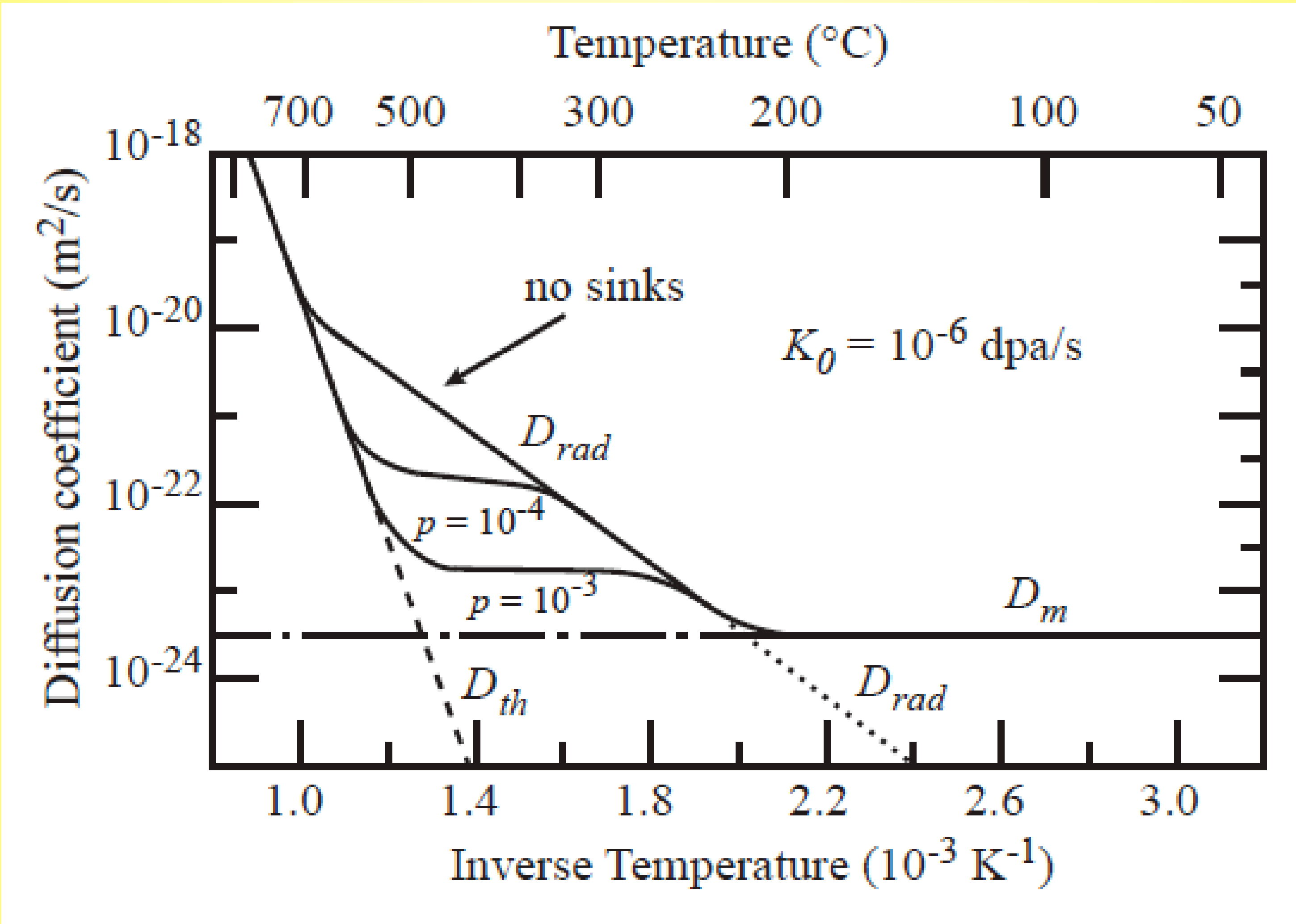
So the vacancy and interstitial populations are not so easy to predict. They're also time dependent.

Vacancy and interstitial populations vary with time



R. Sizemann, JNM 1978

Net result is much higher diffusion of atoms under irradiation



H. Wiedersich, 1986

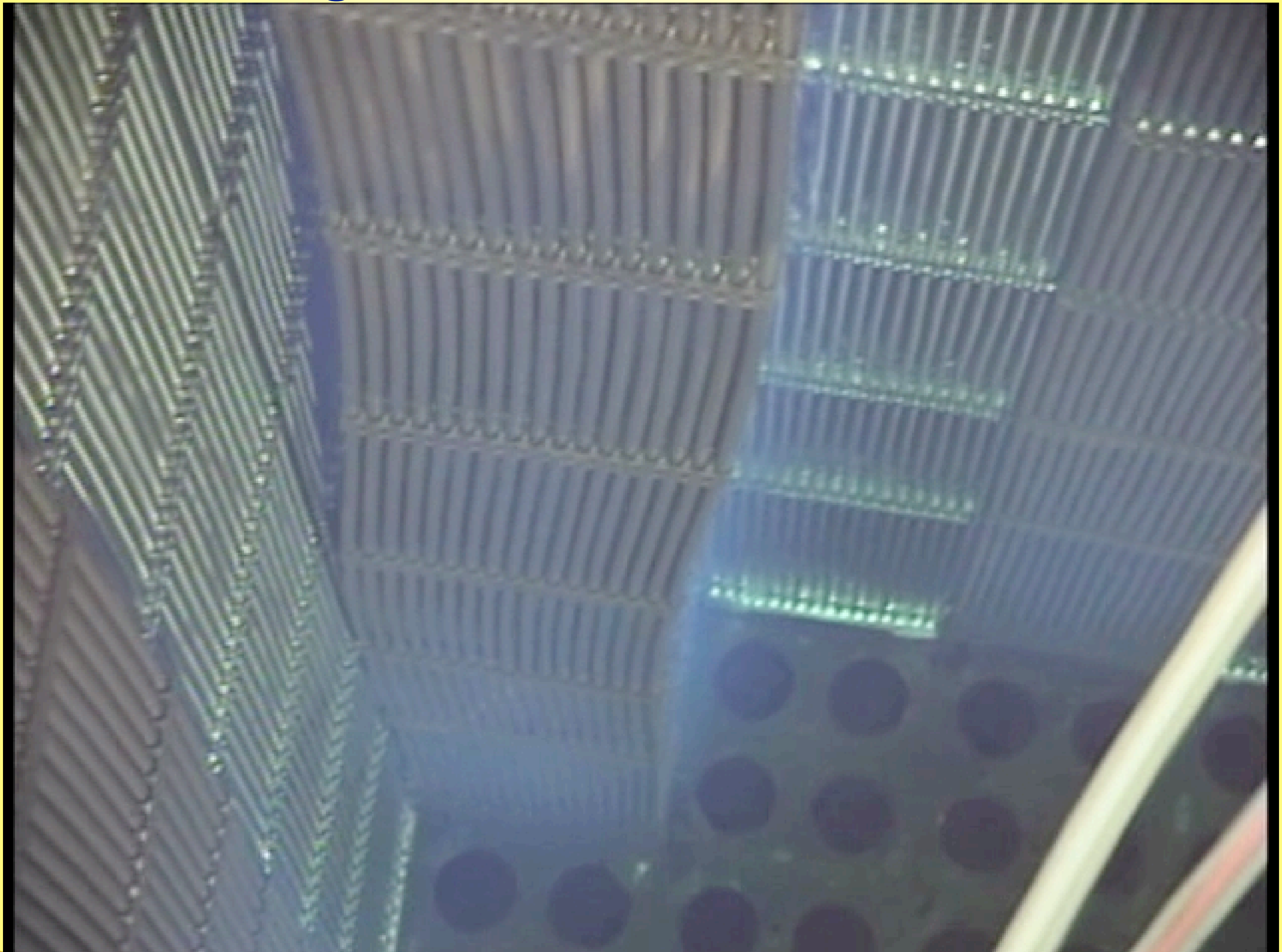
Temperature and dose rate influence point defect populations and their actions

	Effect	Thermal Defect Population	Irrad. Defect Population	Diffusion	Typical Leading Process
Constant Dose Rate	Low Temperature	↓	—	↓	Clustering/ Recomb.
	Moderate Temperature	↑	—	↑	Diffusion
	High Temperature	↑	—	↑	Recomb./ Diffusion
Constant Temperature	Decrease Dose Rate	—	↓	↓	Diffusion/ Clustering
	Increase Dose Rate	—	↑	↑	Clustering/ Recomb.

Consequences of point defect diffusion

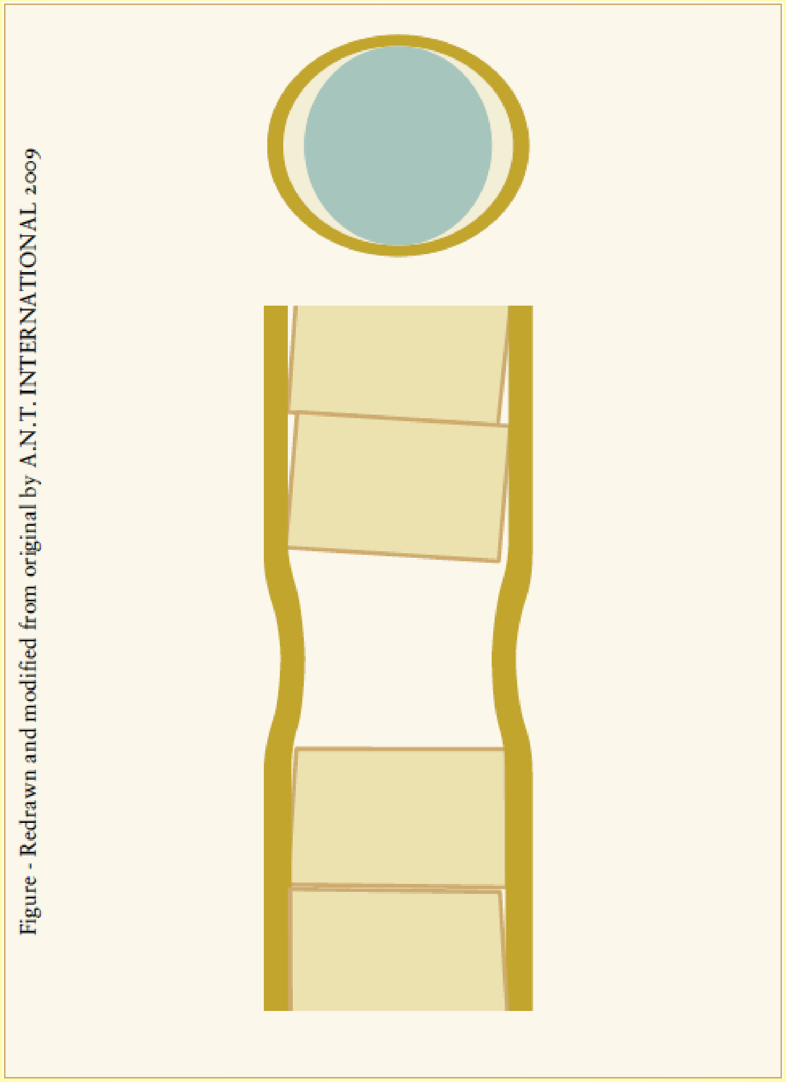
- Growth
- Creep
- RIS
- Radiation induced precipitation
- Dislocation loop formation and growth
- Void formation and growth
- Bubble formation and growth

Irradiation growth - vacancies and interstitials



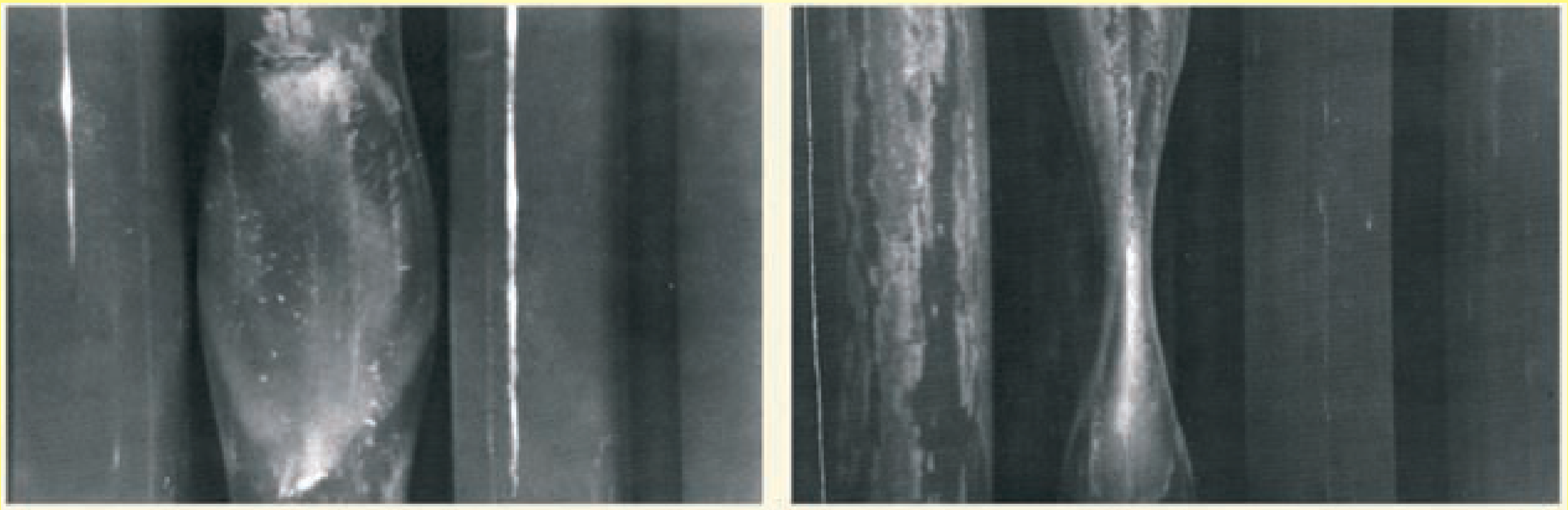
Areva M5 clad fuel assembly

Irradiation creep



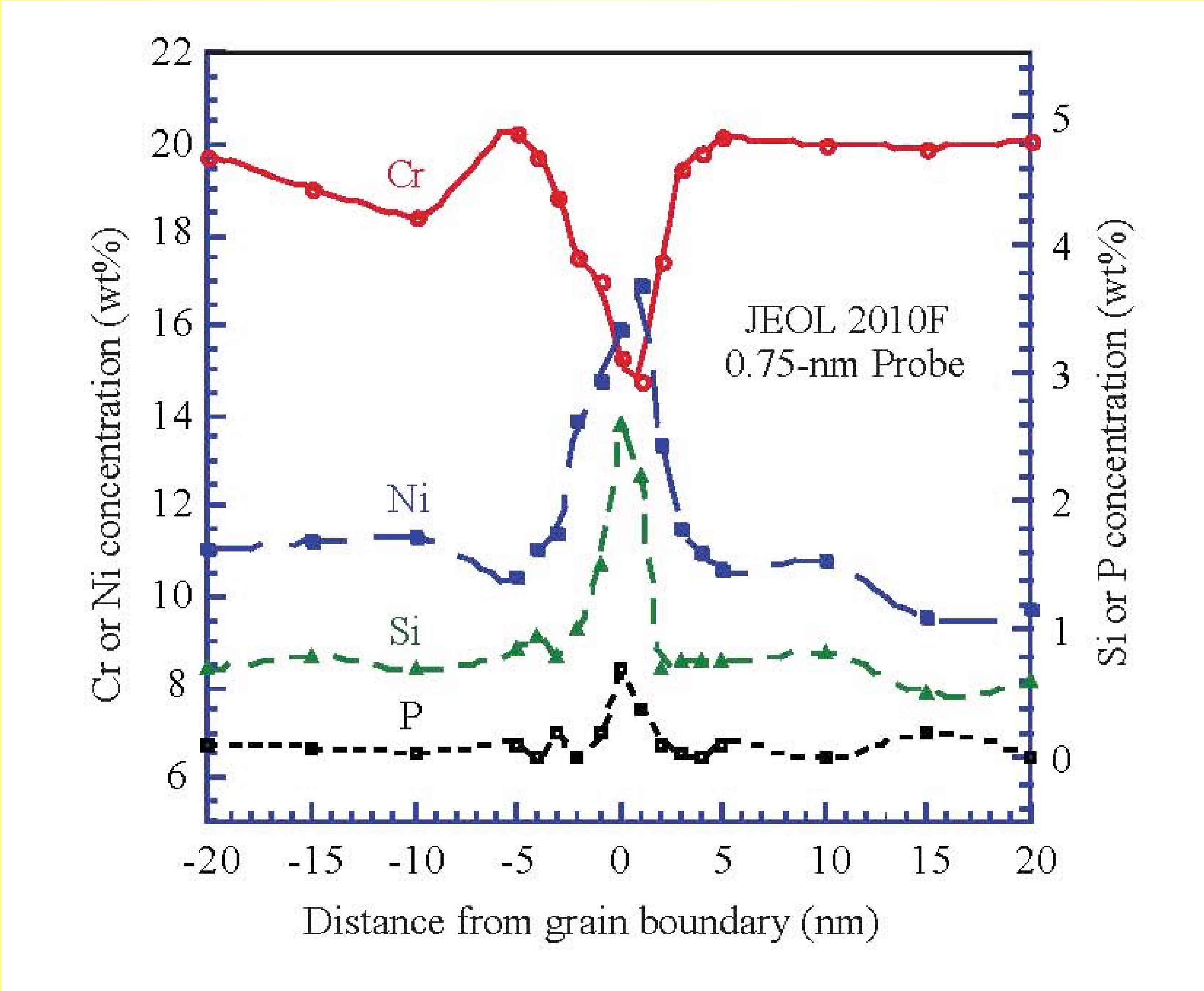
Franklin and Adamson 1988

Irradiation creep



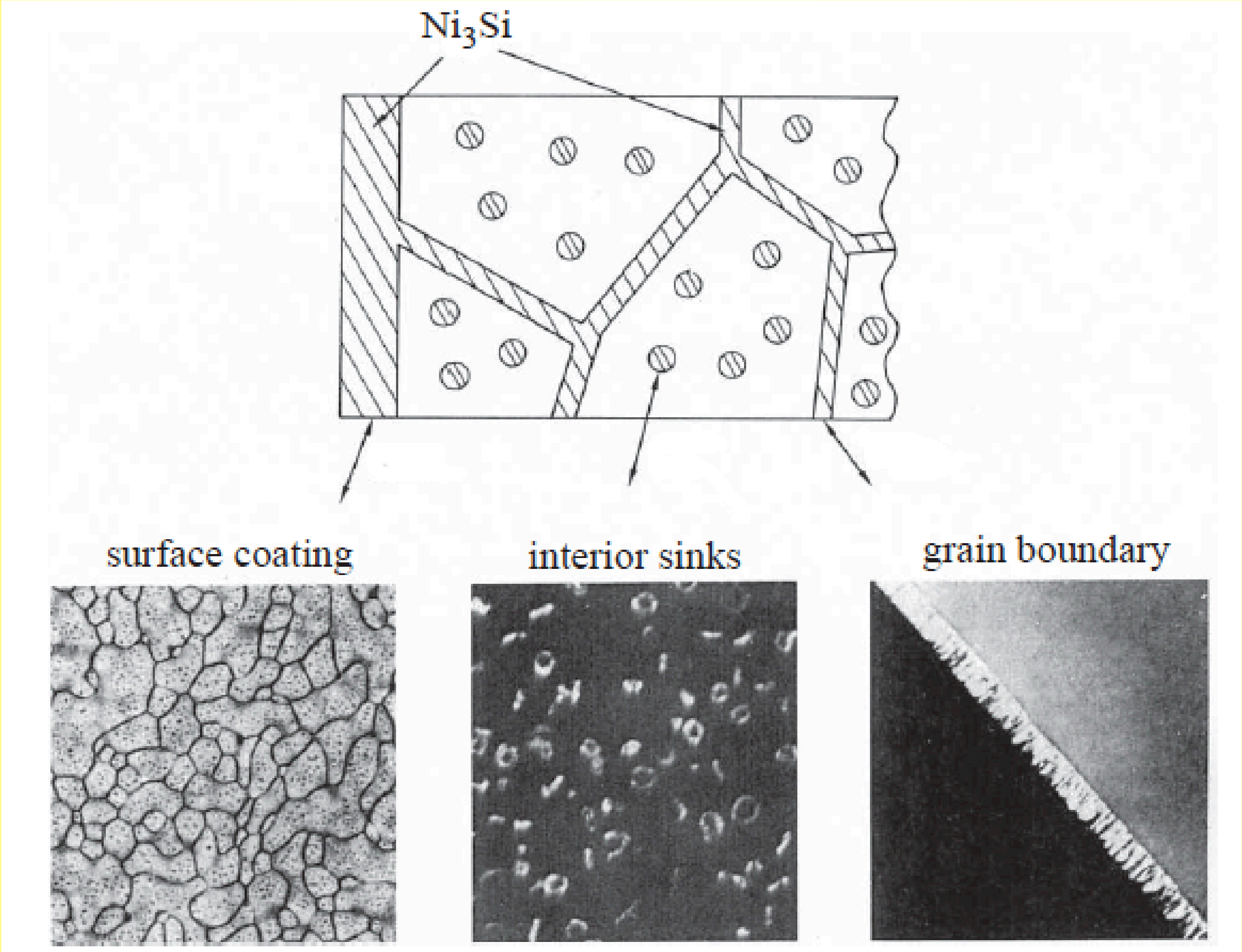
Franklin and Adamson 1988

Radiation-induced segregation



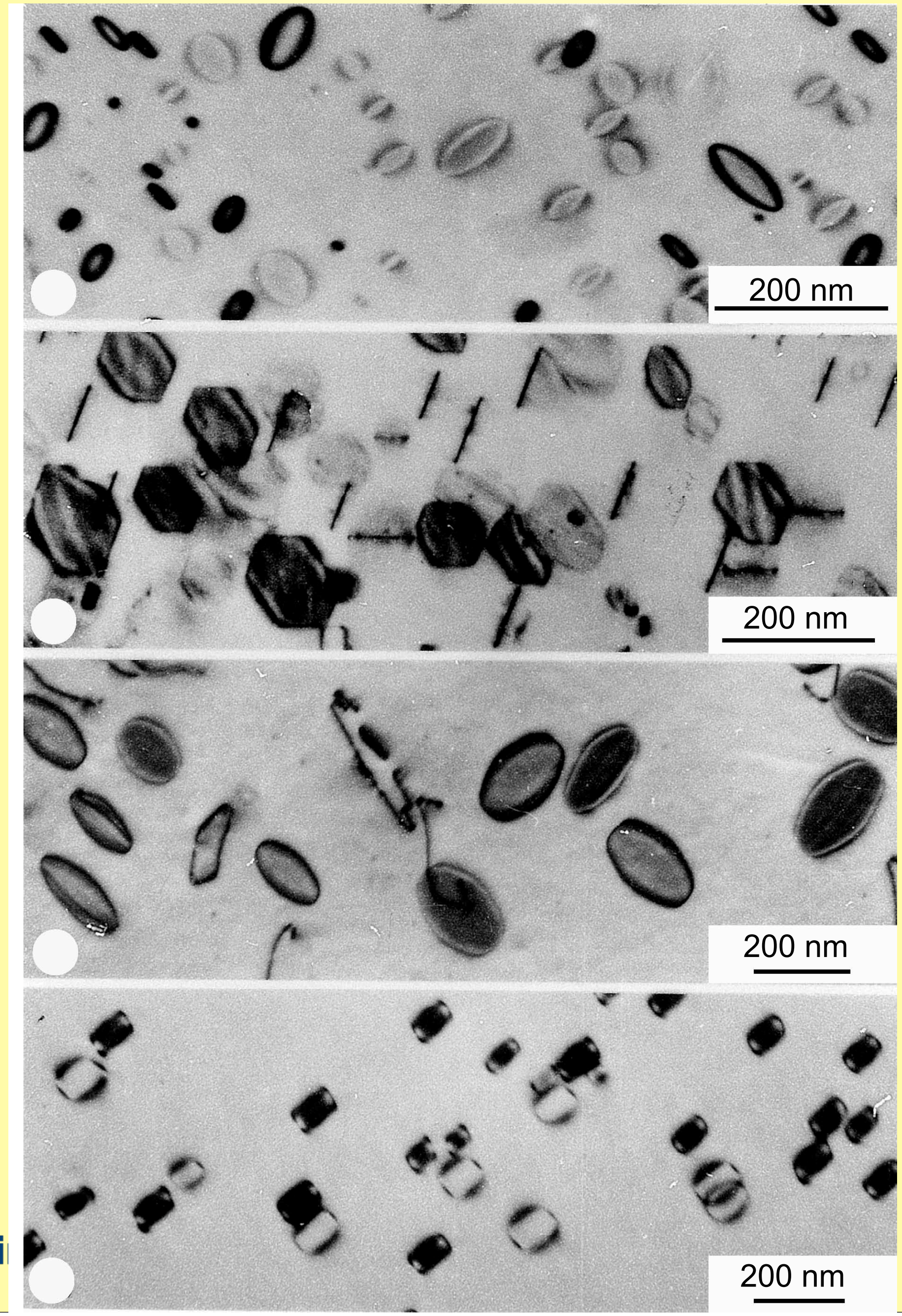
S.M. Bruemmer et al, JNM, 1999

Radiation-induced segregation and precipitation - vacancies and interstitials



L. E. Rehn, Elsevier Science, 1982.

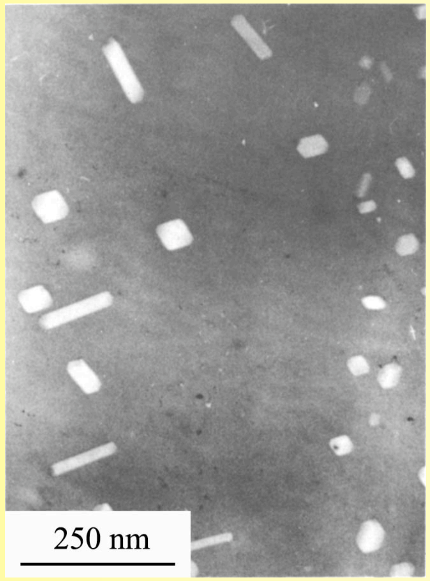
Dislocation loops - clusters of interstitials

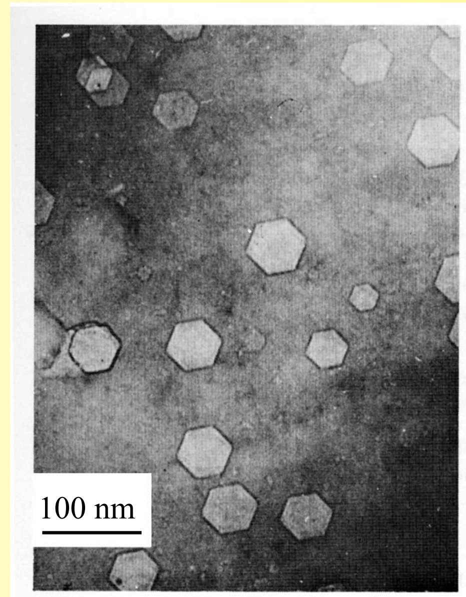


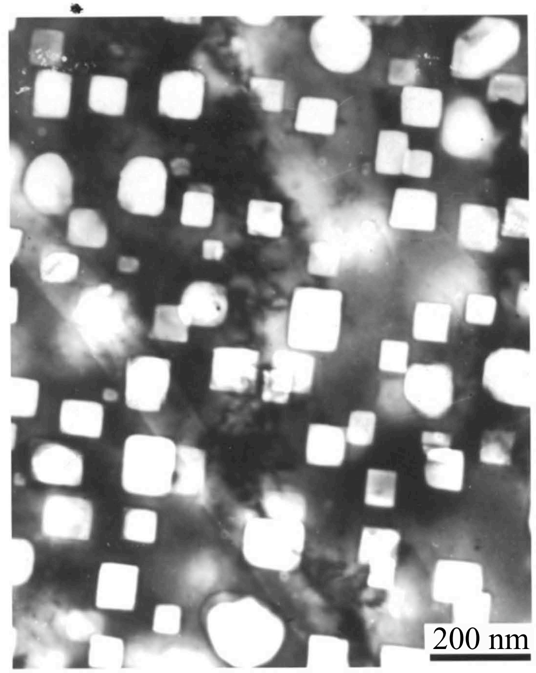
M. Kiritani, JNM 1994

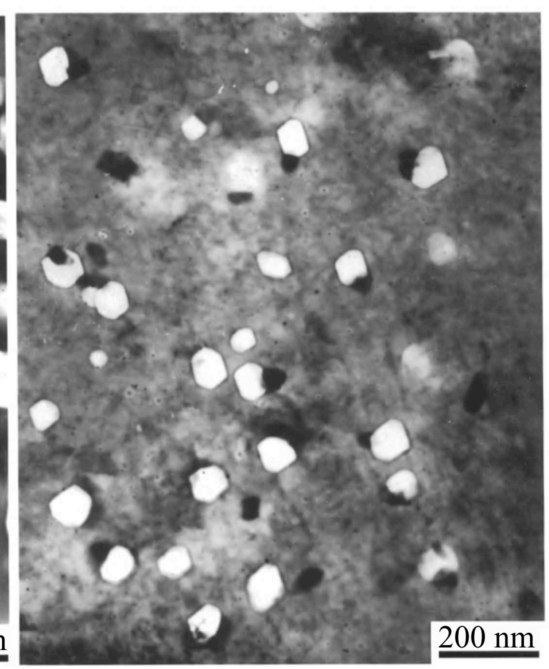
MichiganEngineering

Voids - clusters of vacancies



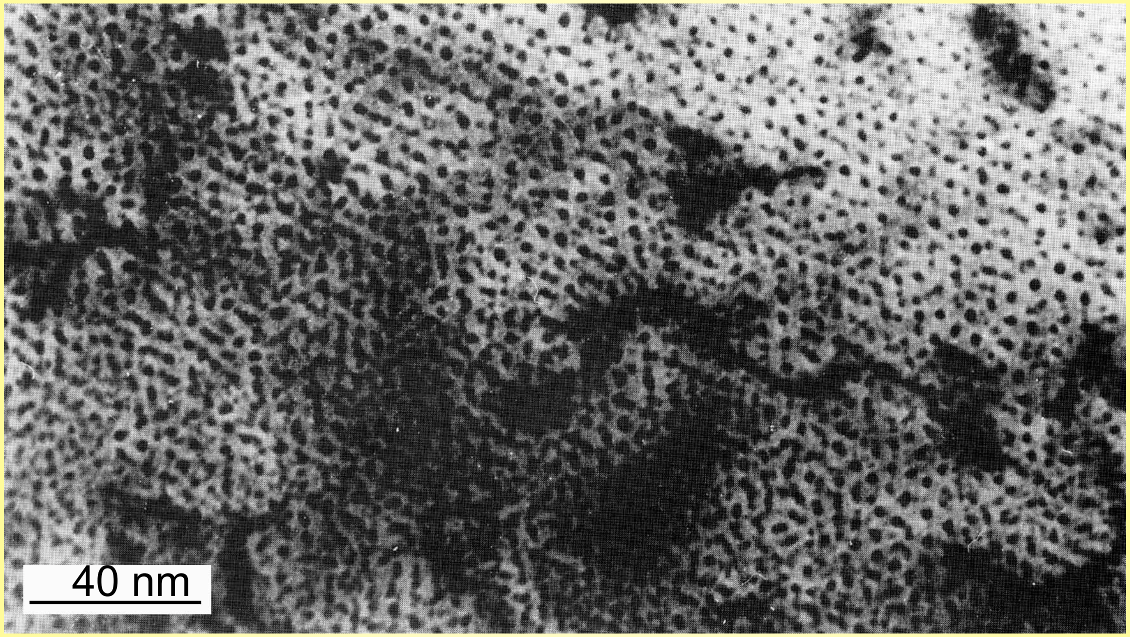






M. Jenkins, et al, 2001 and U. Adda, 1972

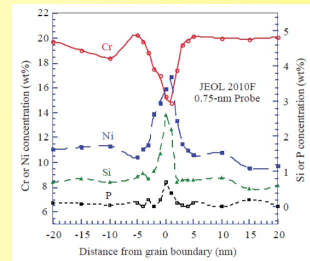
Bubbles - clusters of vacancies with He gas atoms



N.M. Ghoniem, et al, 2002

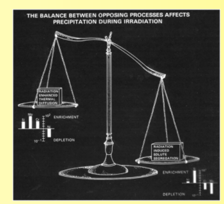
Major forms of radiation damage in reactor structural materials

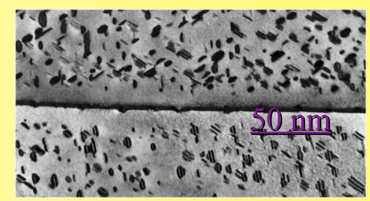
- Radiation induced segregation (<0.4 T_M, >0.1 dpa)



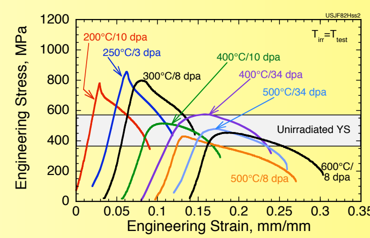
- Volumetric swelling from voids (0.3-0.6 T_M, >10 dpa) and high temperature He embrittlement (>0.5 T_M, >10 dpa)

- Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)





- Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)



- Irradiation creep (<0.45 T_M, >10 dpa)

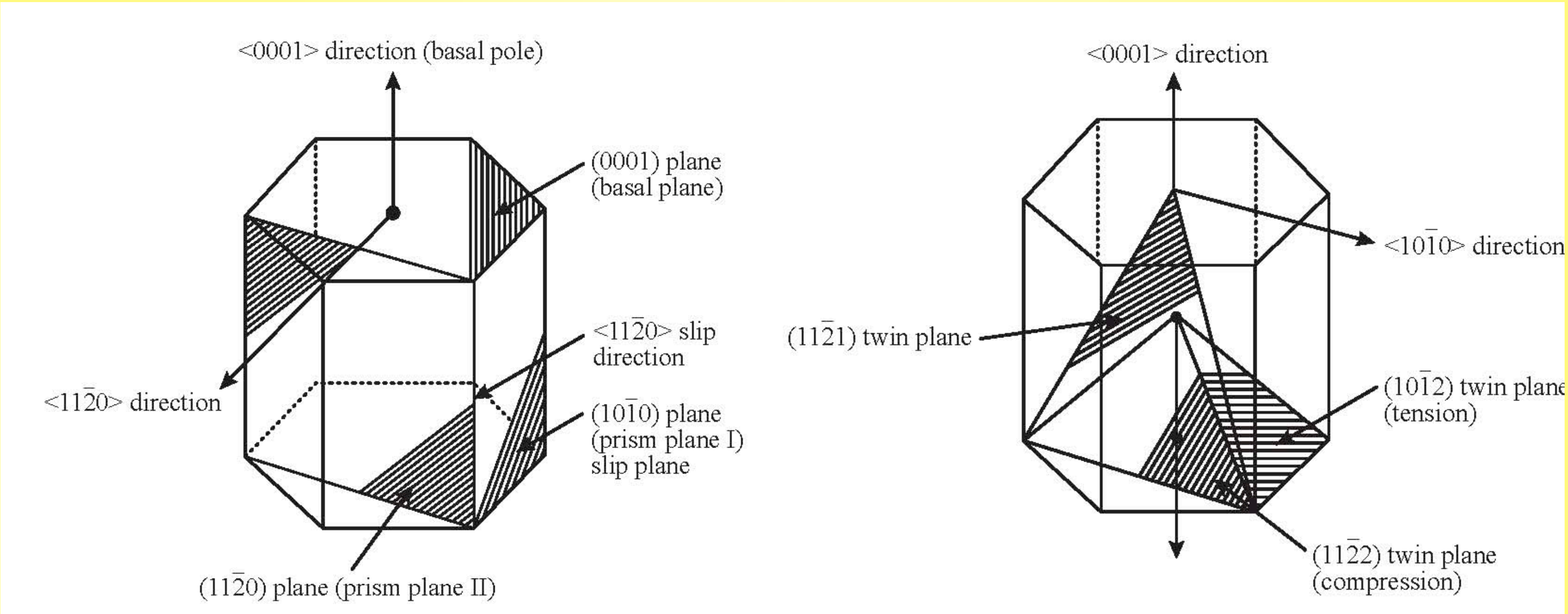
S. Zinkle

Fundamentals of Radiation Damage

Physical Effects of Radiation Damage

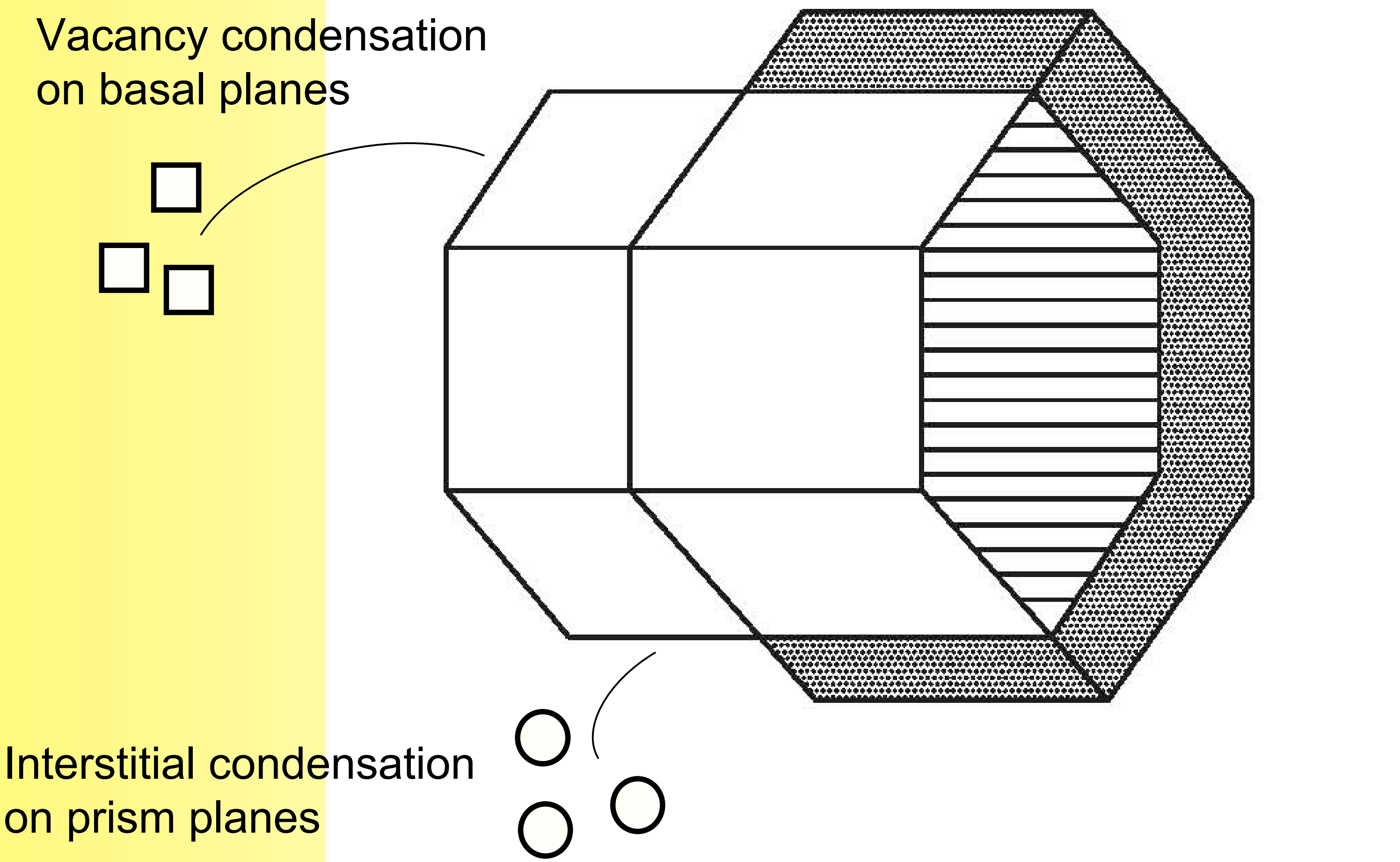
- **Diffusion Driven**
  - Radiation-induced growth
  - Radiation-induced segregation (RIS)
  - Radiation-induced precipitation (RIP)

Growth occurs in anisotropic materials such as Zr alloys

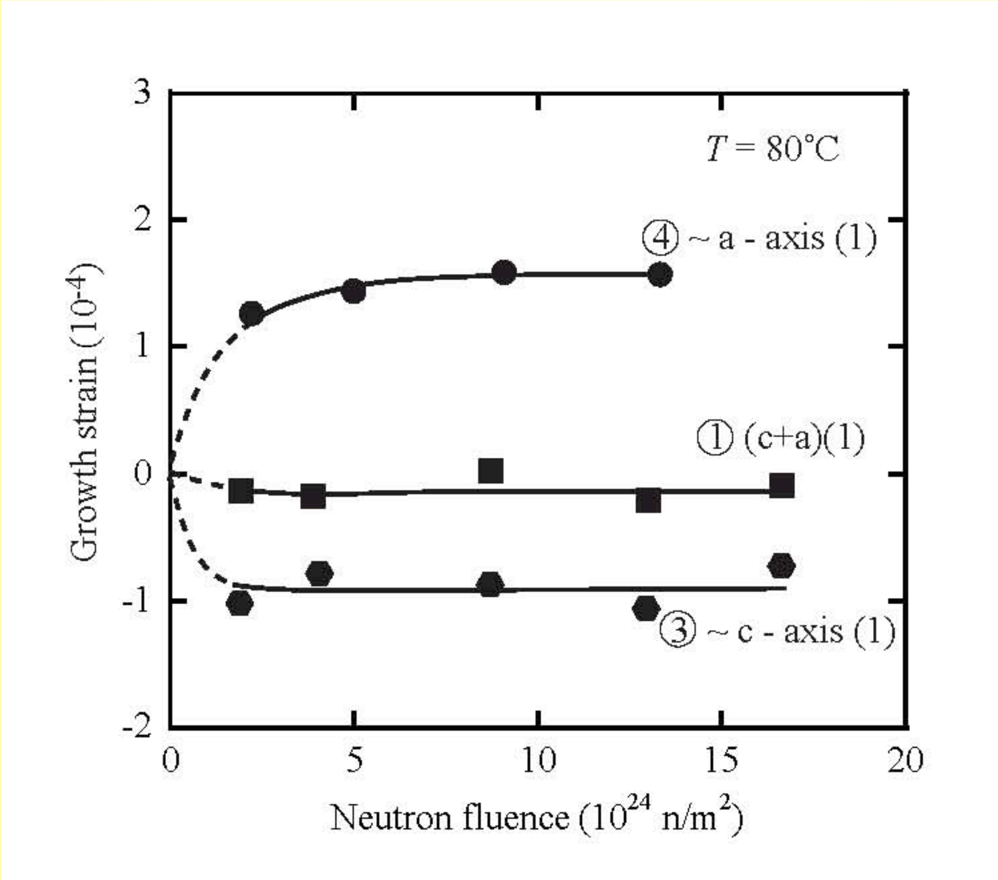


H.H. Klepfer, 1962.

Growth occurs by partitioning of vacancies and interstitials to different planes

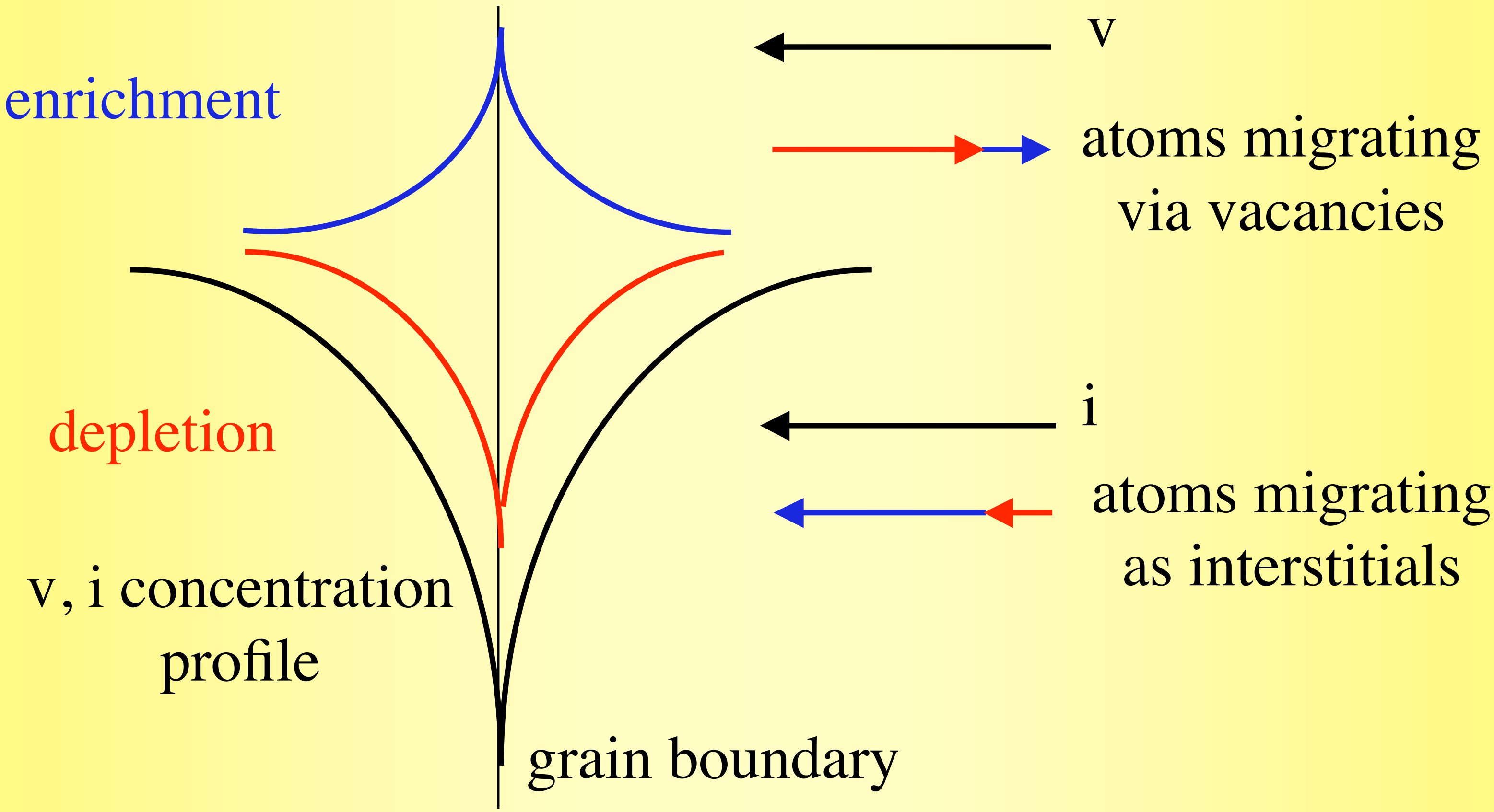


Growth-induced strains vary greatly depending on orientation



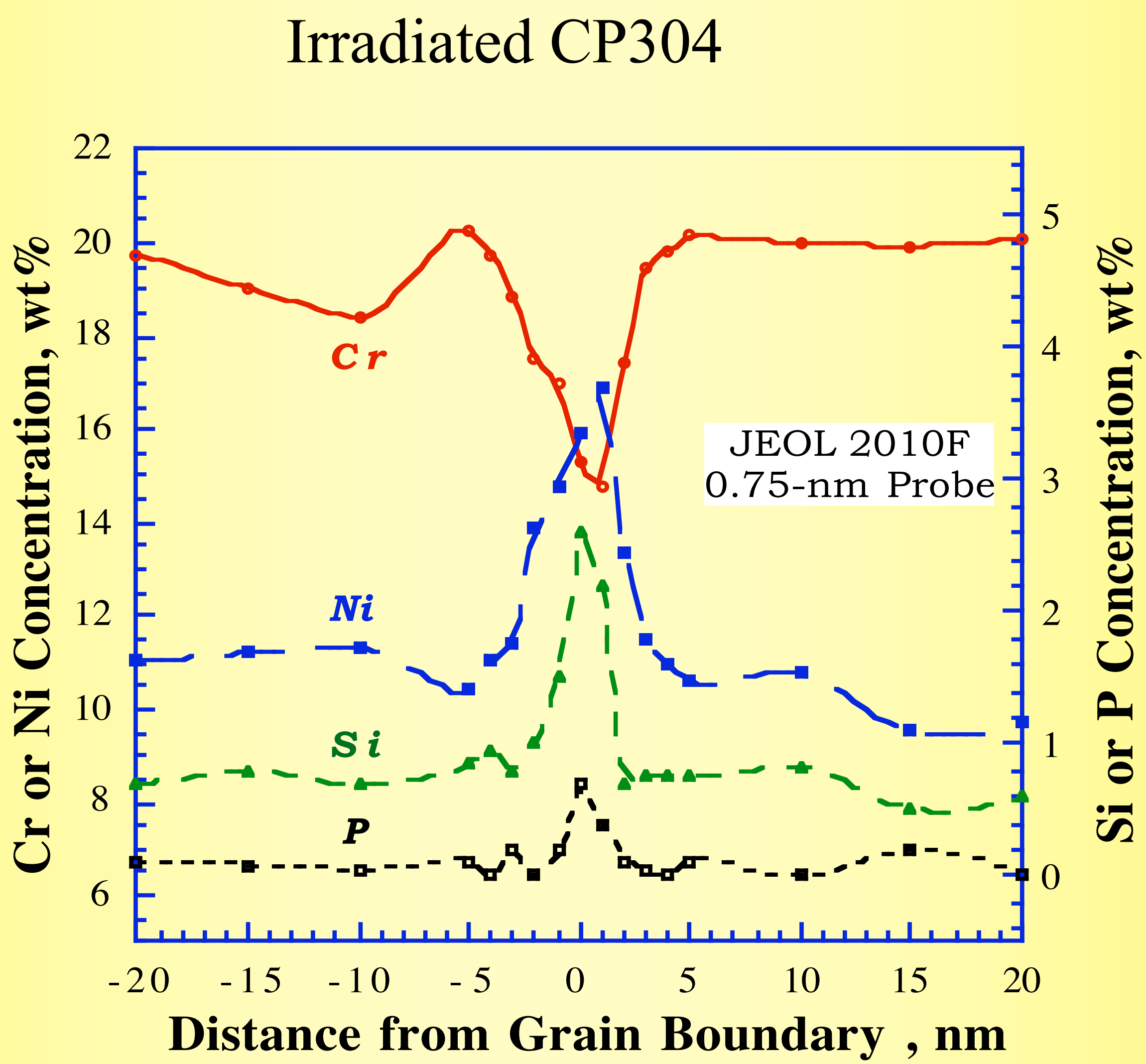
GJC Carpenter et al, JNM, 1988

Radiation-Induced Segregation



- **High concentrations of radiation-induced defects will migrate to defect sinks.**
- **Any preferential association between an atom and one type of defect will result in segregation.**

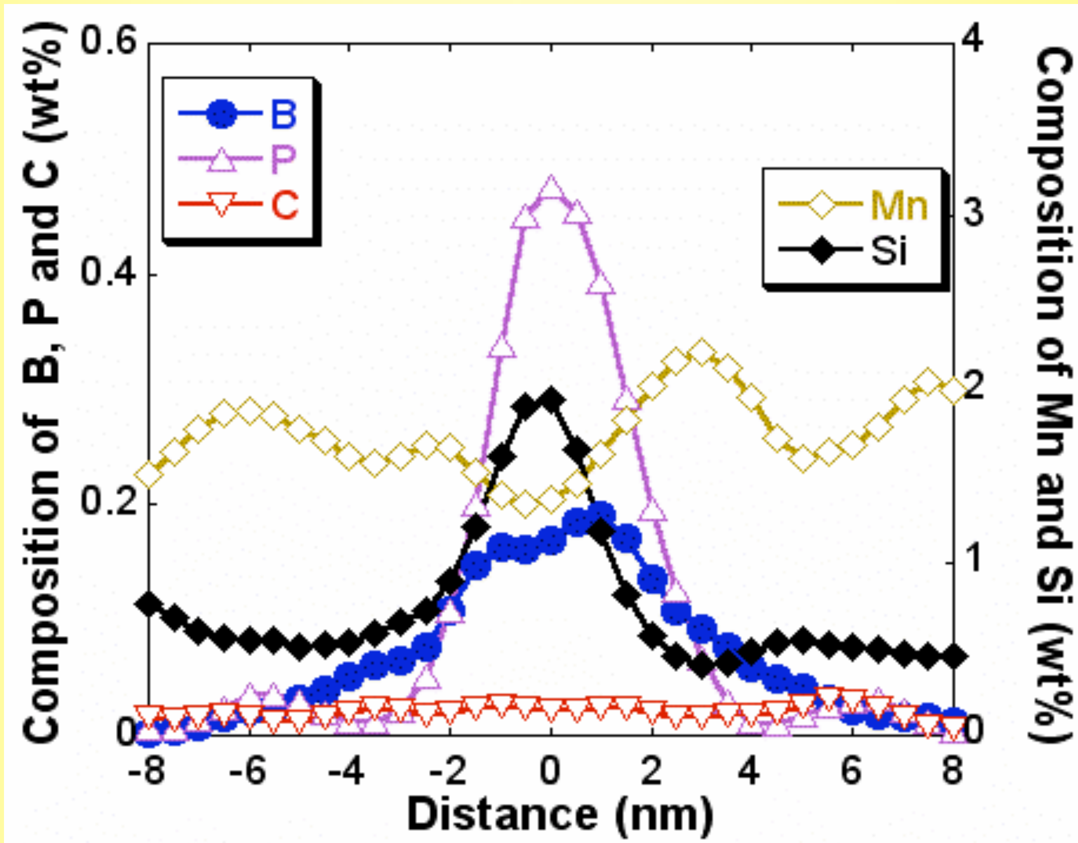
Radiation Induced Segregation



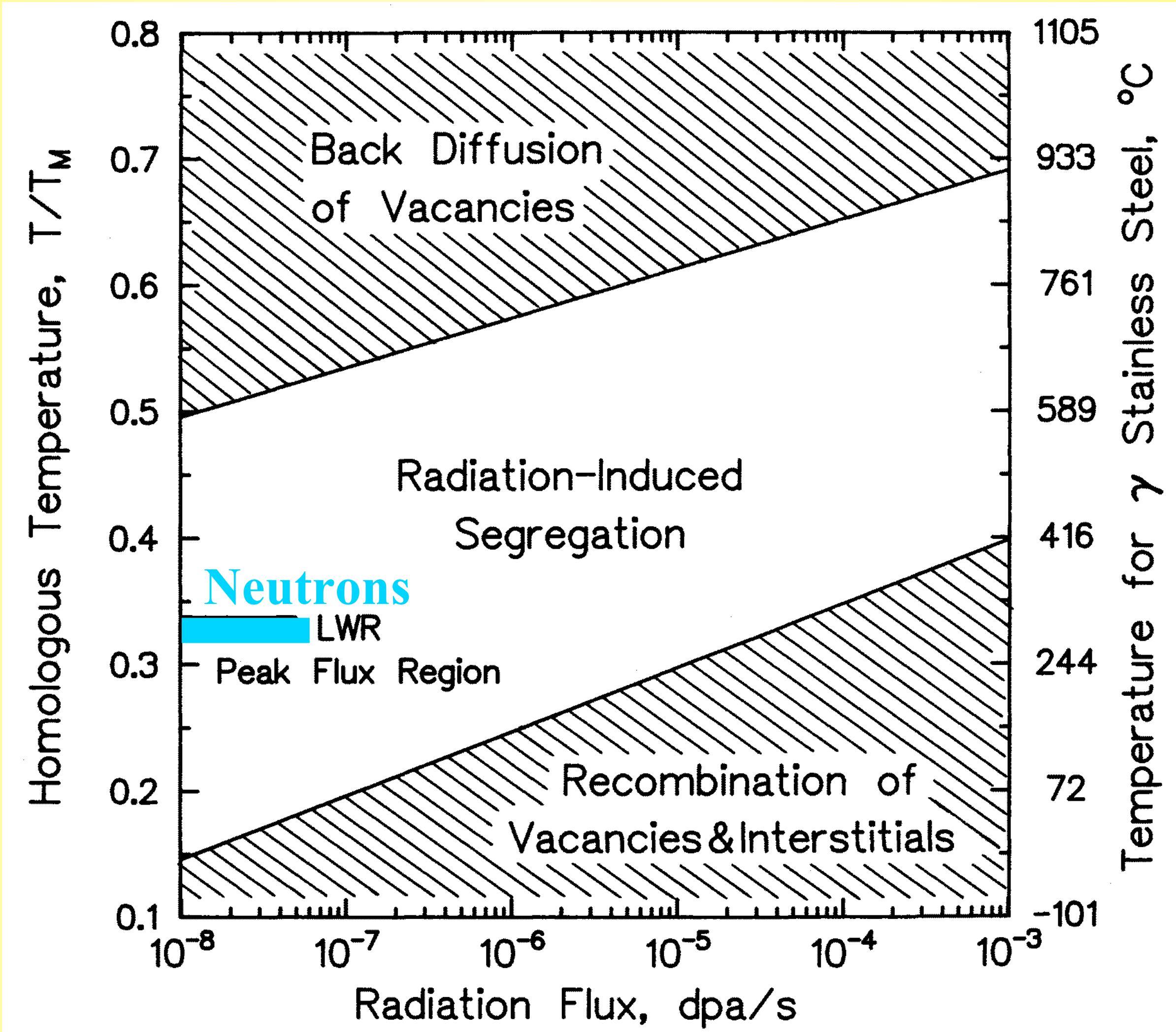
S.M. Bruemmer et al, JNM, 1999

Radiation Induced Segregation

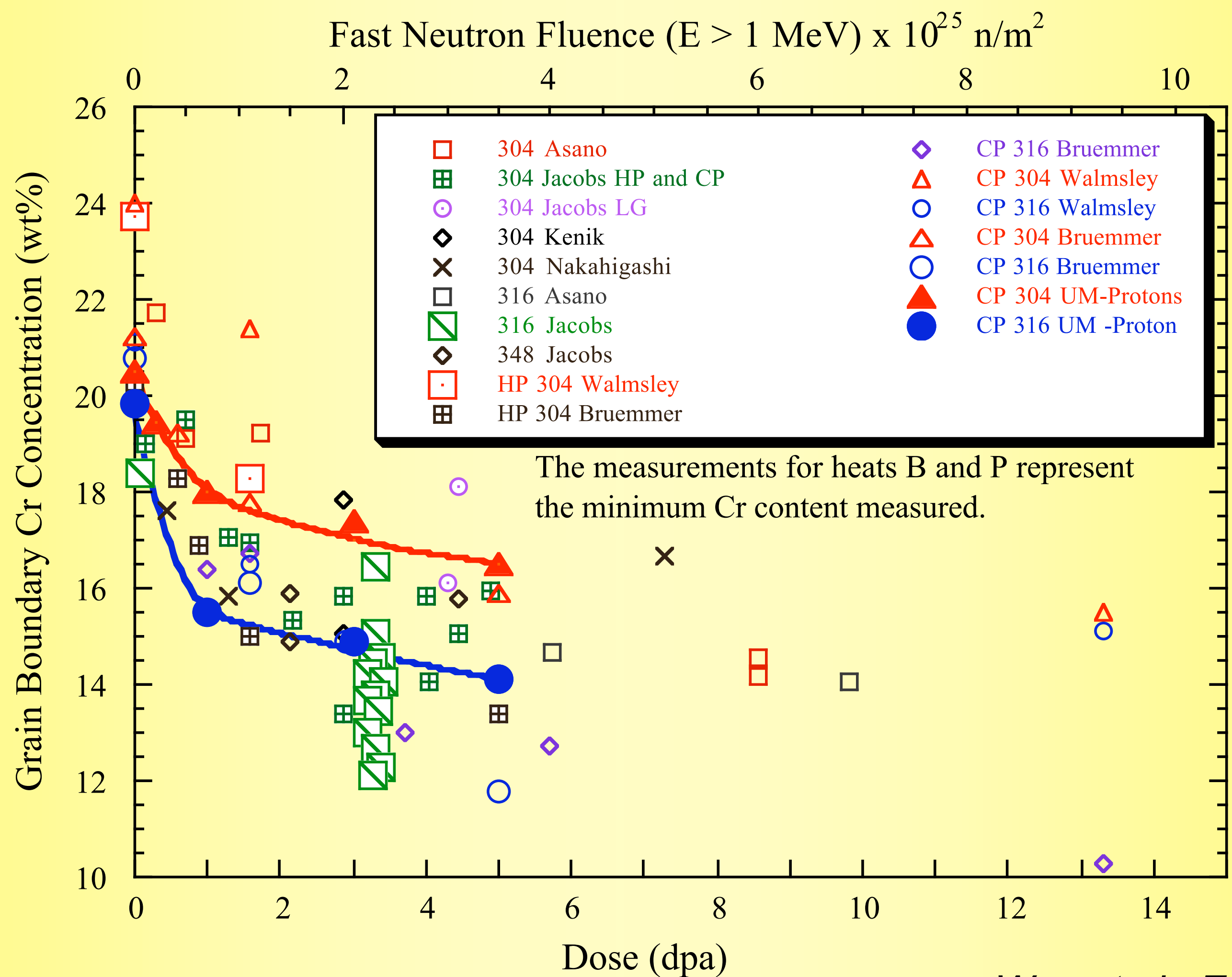
Irradiated CP304



Temperature-displacement rate relationship in RIS for various particle types

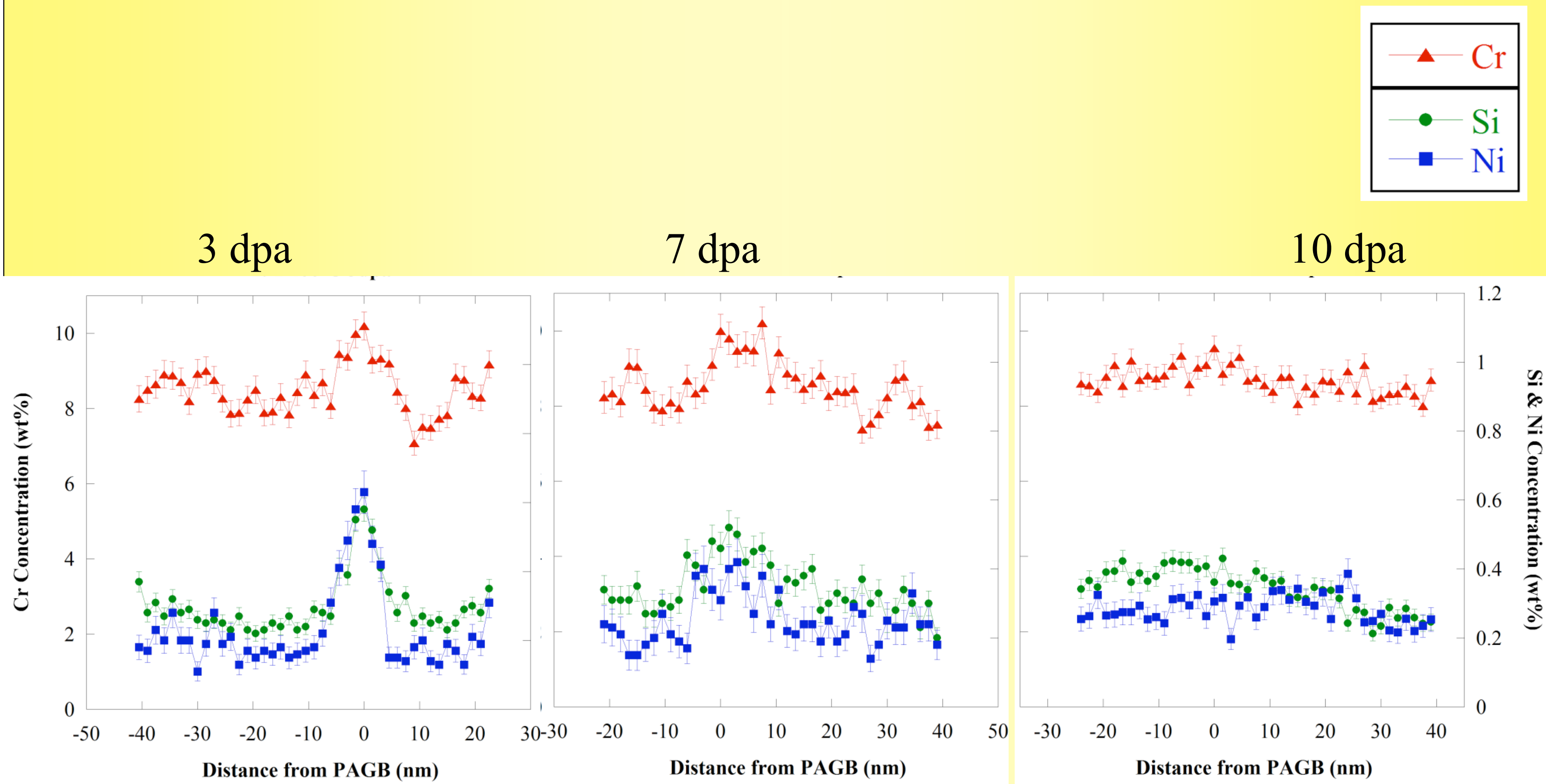


Chromium depletion as a function of dose for 360°C proton irradiations

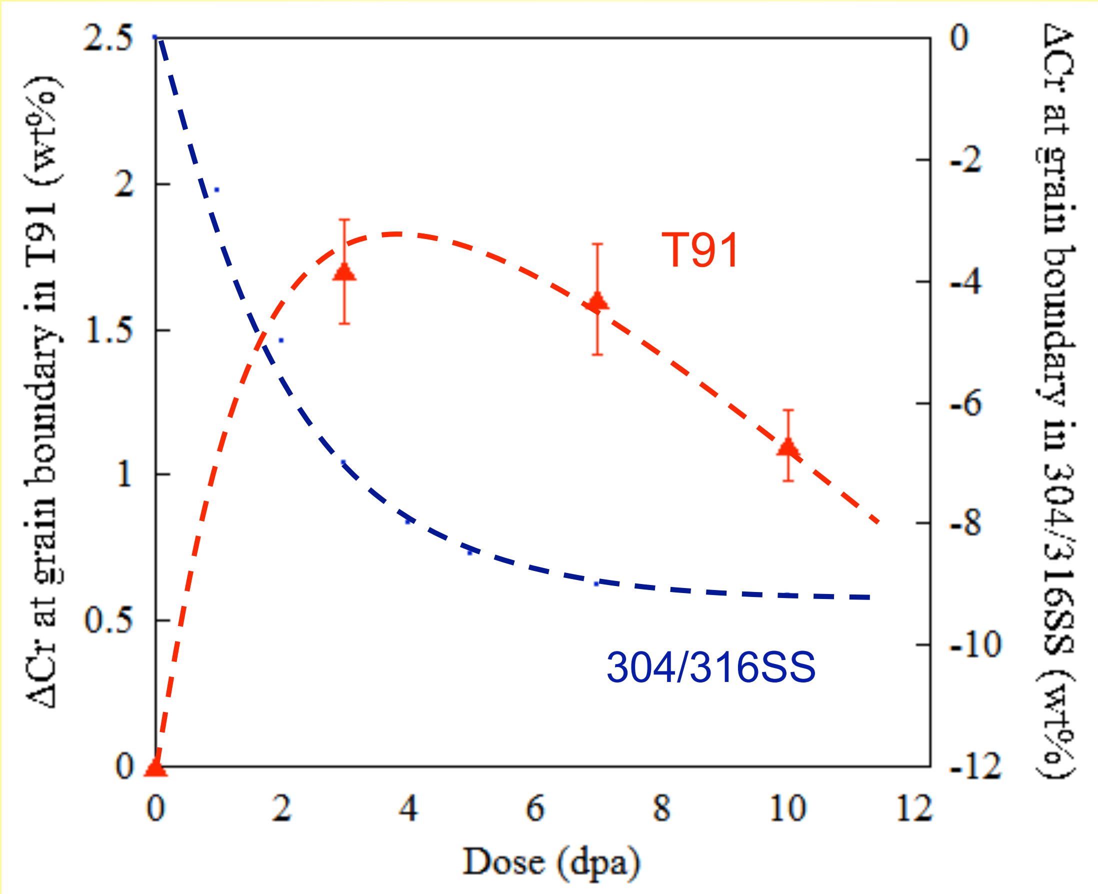


Was et al., Env. Deg., 2003

Grain boundary segregation at PAGBs in T91 following irradiation to 7 dpa at 400ºC

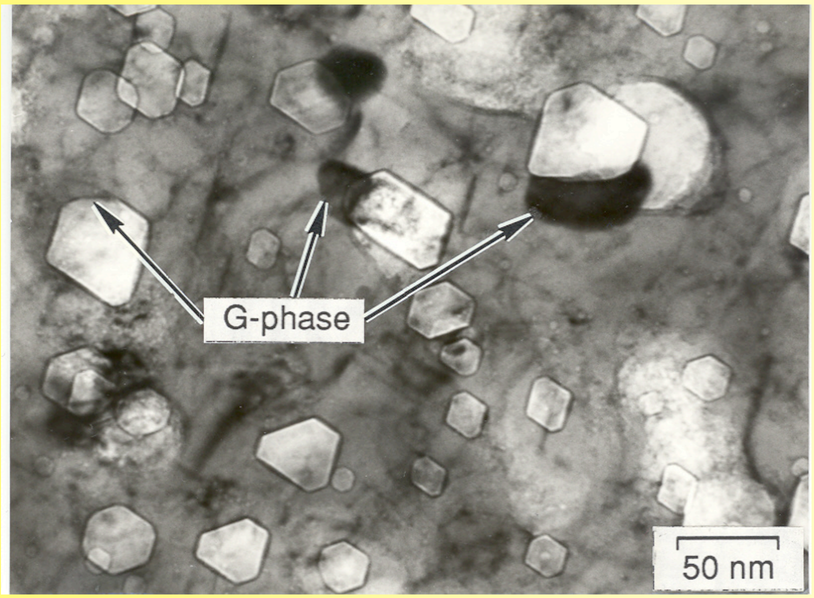


RIS in T91 at 400°C vs. austenitic alloys at ~ 300°C



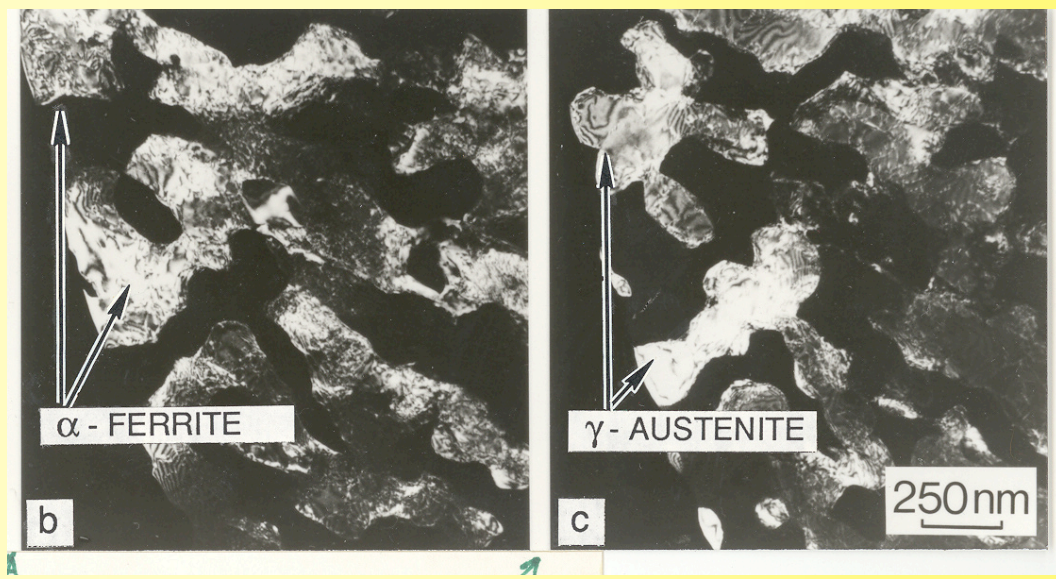
Z. Jiao et al., JNM 2010

Radiation-Induced Segregation Can Lead to Precipitation

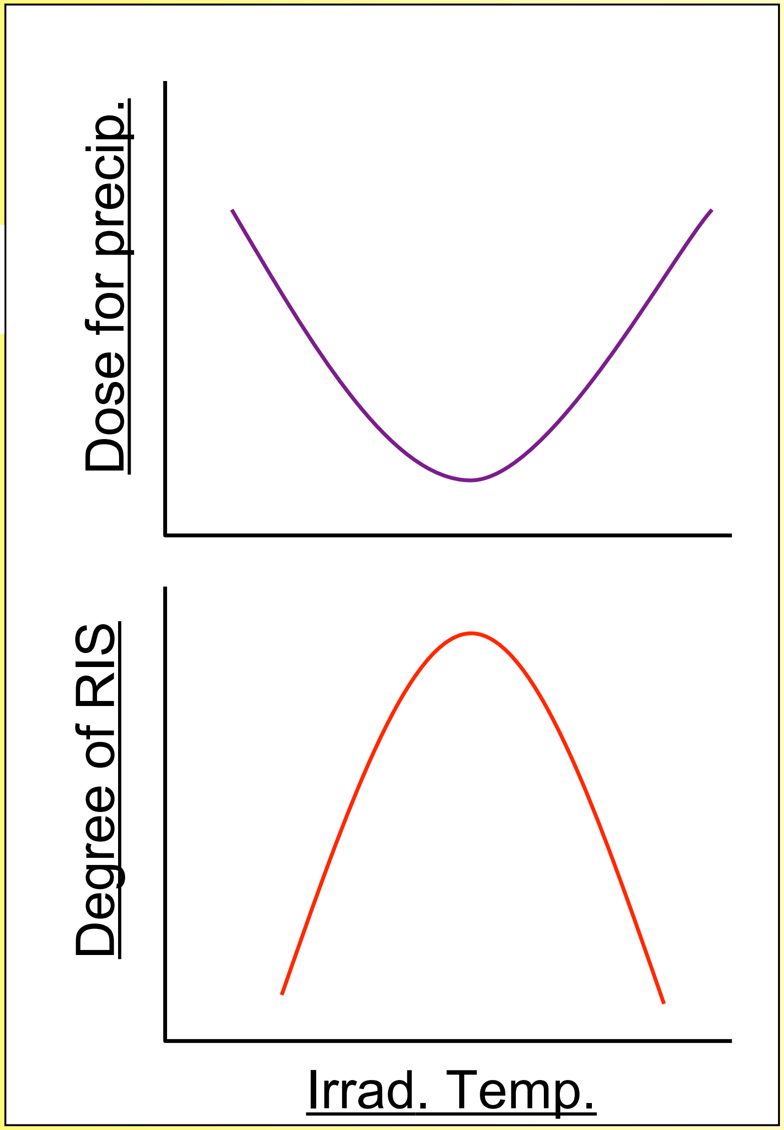


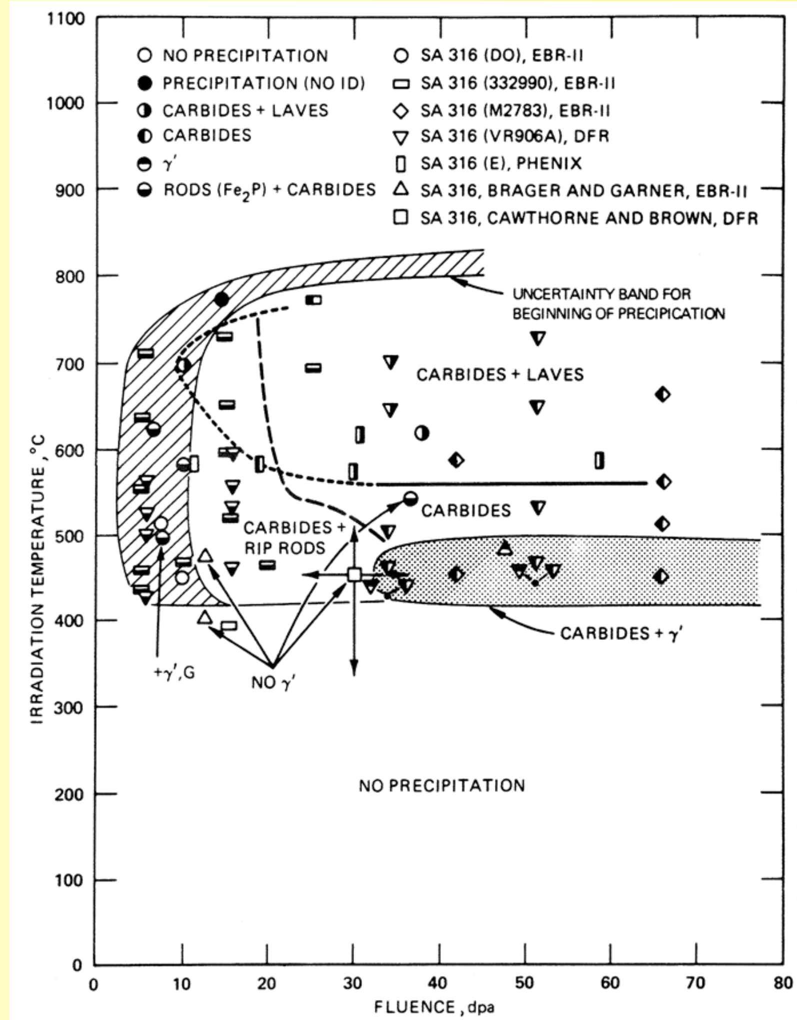
- Microstructure of SA Fe-12Cr-15Ni-1Si austenitic stainless alloy irradiated in EBR-II at 575°C (<20 dpa), with TEM showing
- RIS causes the initially homogeneous γ-austenite matrix to decompose into Fe-Cr-Si ferrite and Fe-Ni austenite.

SA PCA steel irradiated at 500 C in ORR to 11 dpa (200 appm He), showing the association between radiation-induced G-phase silicide ($Mn_6Ni_{16}Si_7$) particles and the largest voids



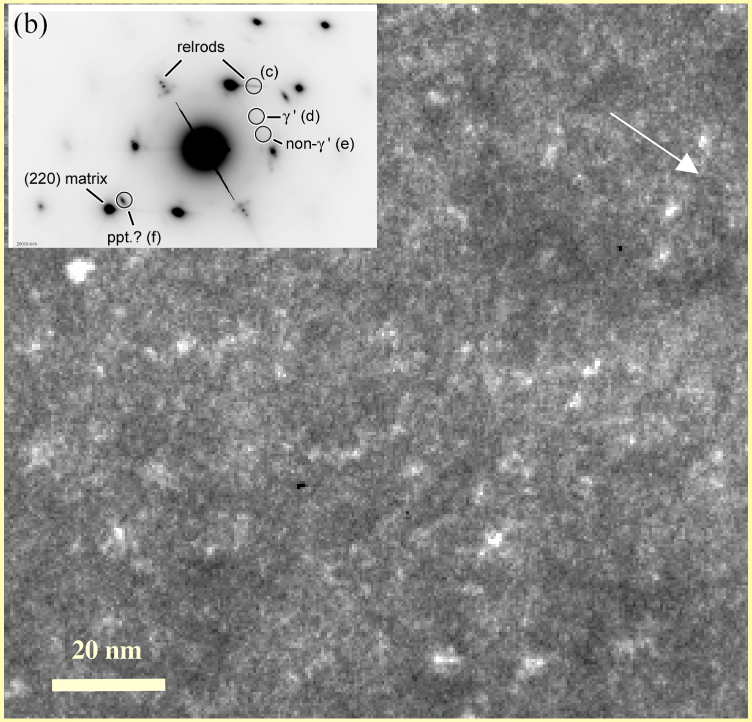
RIS and RIP will be very sensitive to the operating conditions





RIS and RIP have been widely observed in 316 SS alloys, and occurs in many other alloy systems.

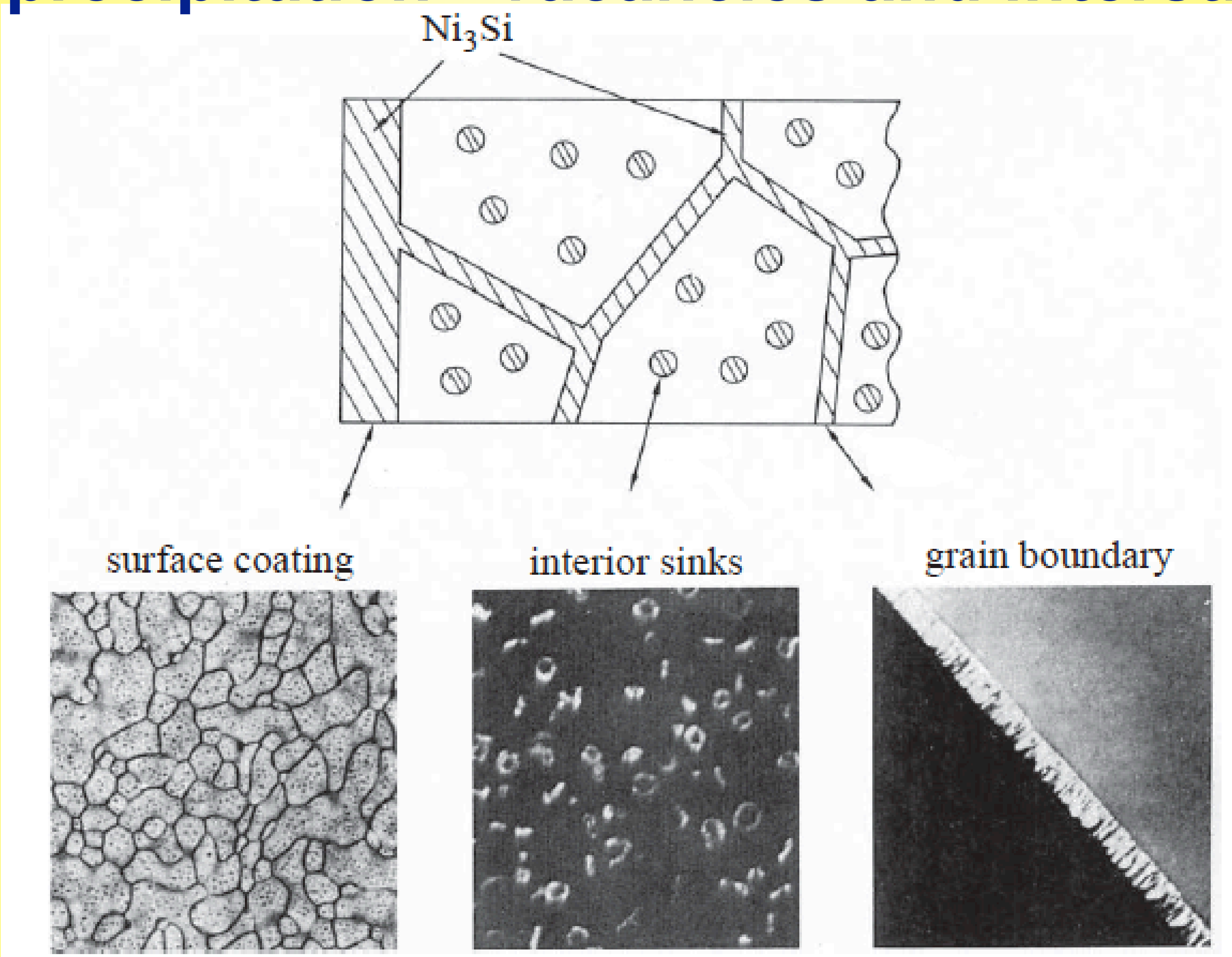
Precipitation of γ' in neutron-irradiated stainless steel baffle bolt



Tihange baffle bolt:
neutron-irradiated to ~7 dpa
at 299°C*.

•ATEM Characterization of Stress-Corrosion Cracks in LWR-Irradiated Austenitic Stainless Steel Core Components, PNNL EPRI Report, 11/2001.
•Image resized for equivalent scale.

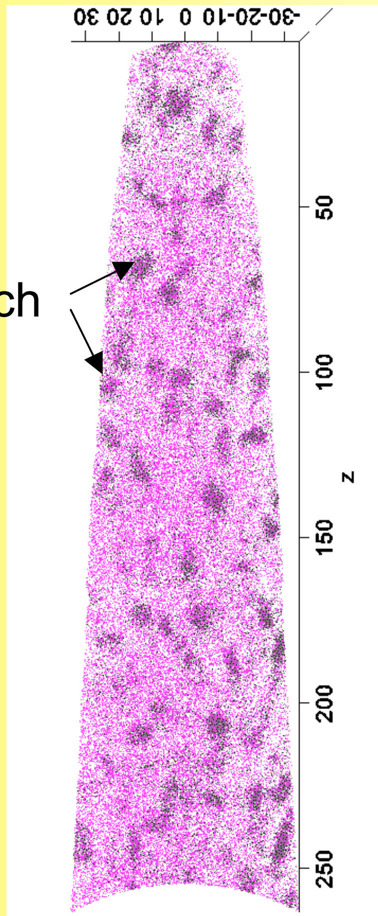
Radiation-induced segregation and precipitation - vacancies and interstitials



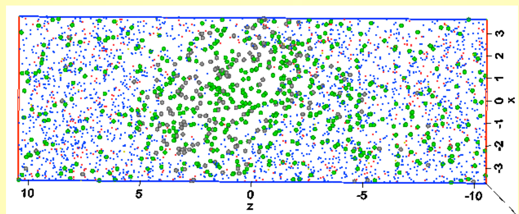
L. E. Rehn, Elsevier Science, 1982.

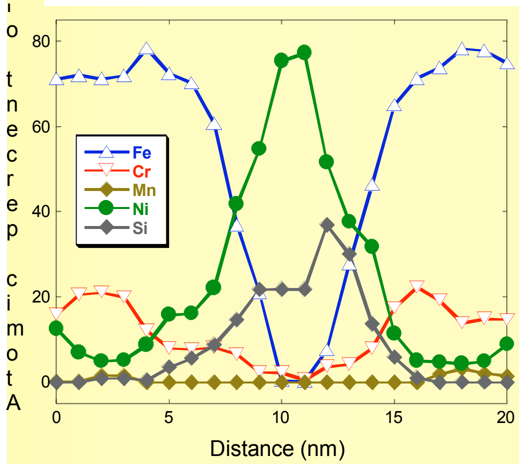
Ni/Si- rich clusters irradiated 304SS containing Si (5 dpa at 360°C)

Ni/Si- rich clusters



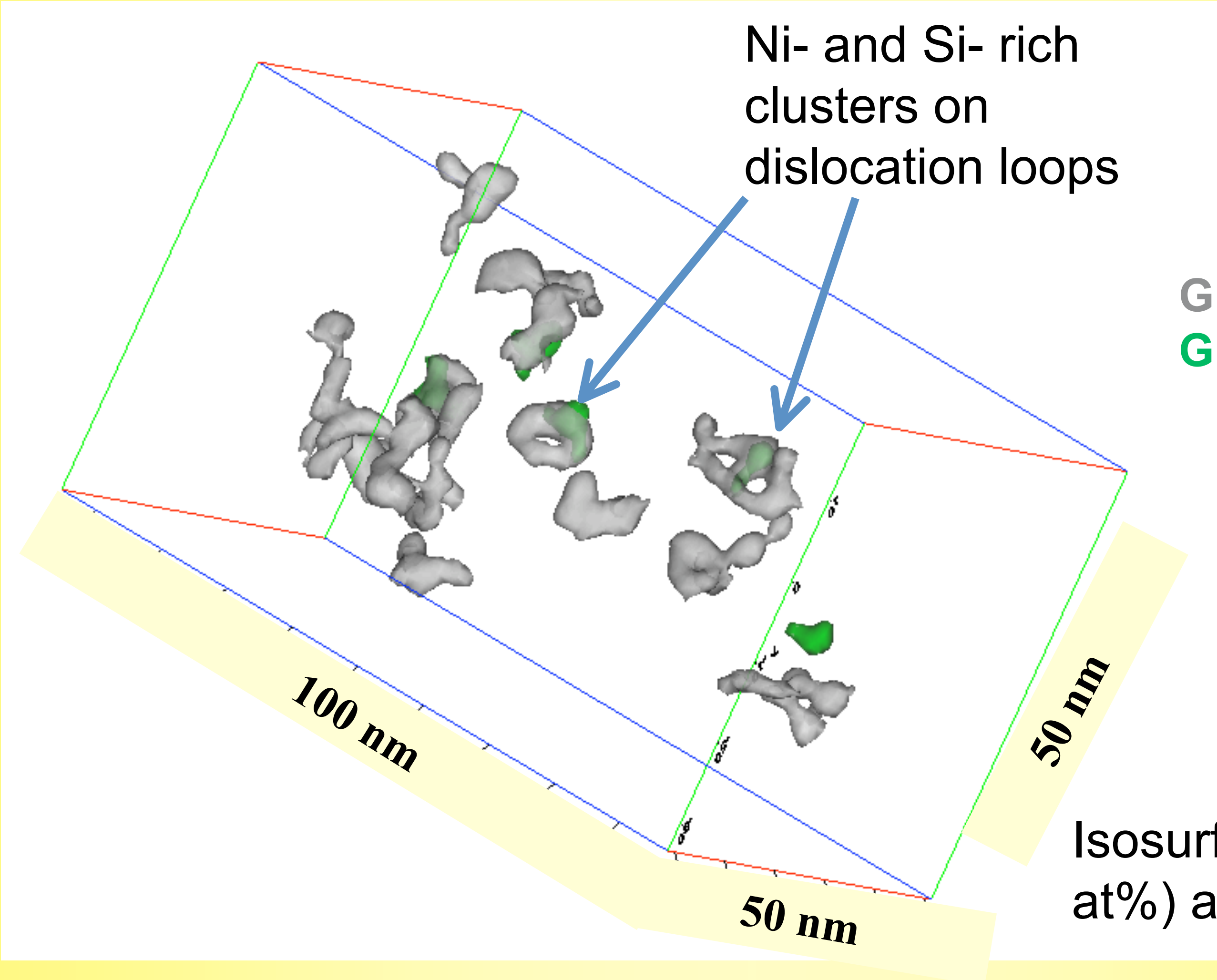
Irradiated HP304+Si





- Ni/Si- rich clusters were found in both irradiated HP304+Si and CP304 in the matrix.
- The Ni/Si ratios of the clusters varies from cluster to cluster.
- Some clusters have a core (1-2 nm) with Ni/Si close to 3:1, which is probably the Ni_3Si (γ') phase.

Ni/Si- rich clusters associated with dislocation loops in CP304 irradiated to 5 dpa at 360°C

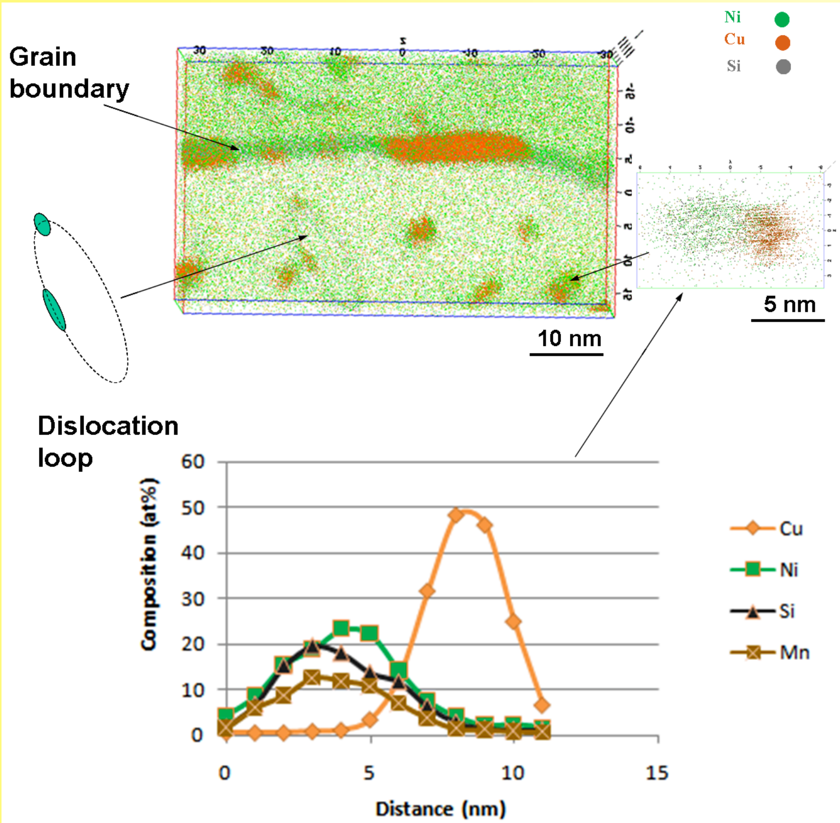


Ni- and Si- rich clusters on dislocation loops

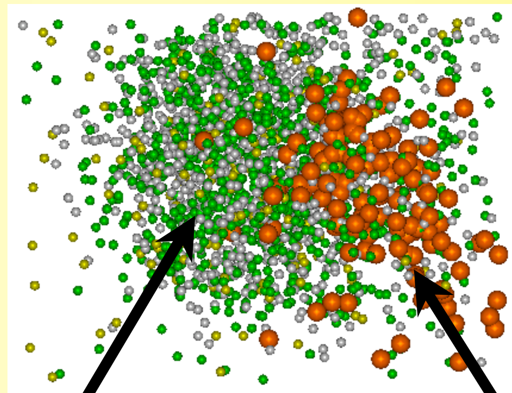
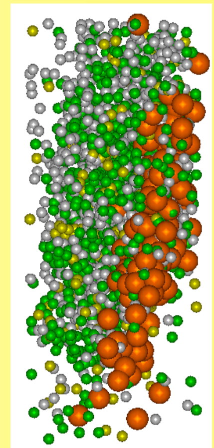
Grey: Si
Green, Ni

Isosurfaces of Si (3 at%) and Ni (20 at%)

Precipitates in HCM12A irradiated to 7 dpa at 400°C



Different views of same precipitate

Ni-Si-Mn- rich

Mainly Cu- rich

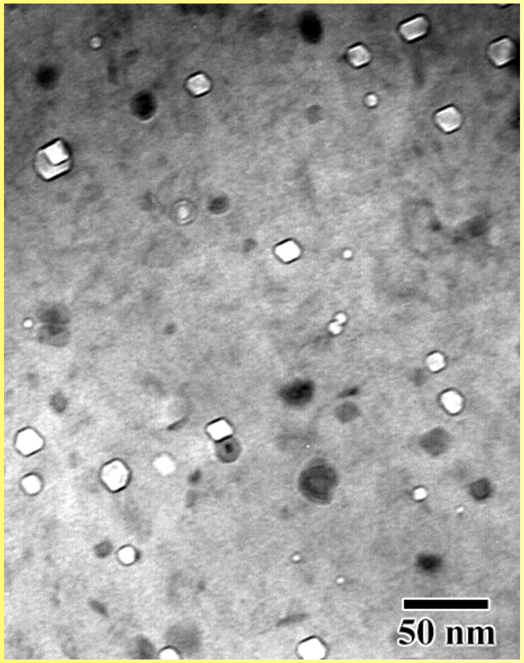
Size: ~3-4 nm Number density: ~6 x 10^{22} m^{-3}

Fundamentals of Radiation Damage

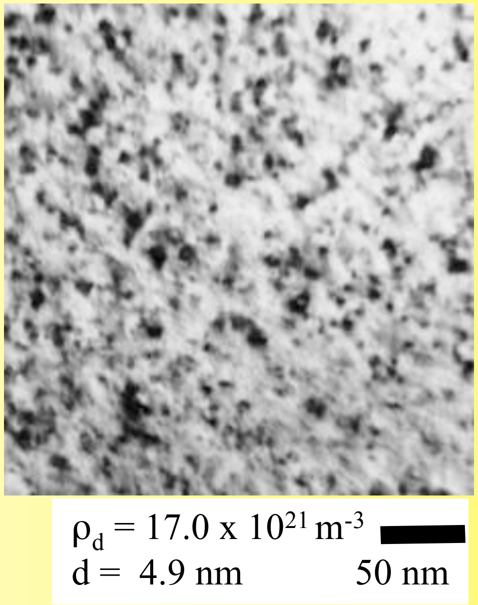
Physical Effects of Radiation Damage

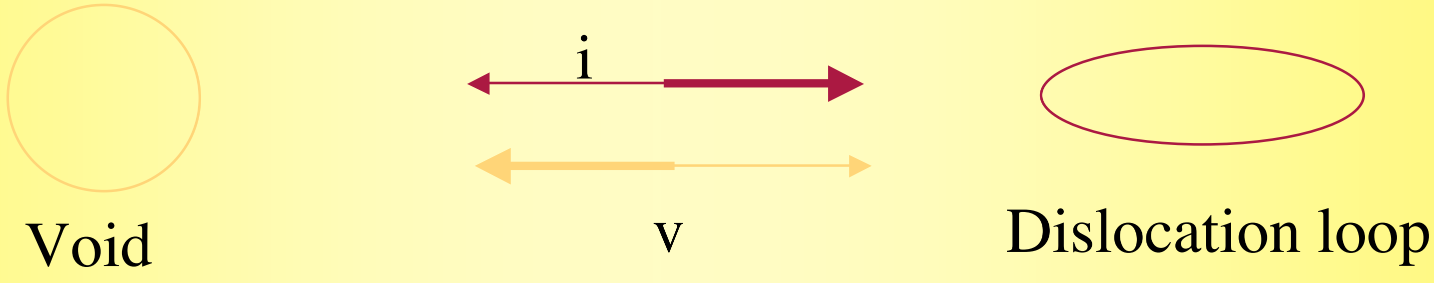
- **Clustering**
  - Interstitial clustering into dislocation loops
  - Void formation and swelling
  - Bubble formation

Clusters: voids and dislocation loops



- Process
  - Radiation produces point defects
  - Interstitials migrate preferentially to dislocations leaving excess vacancies to form voids
  - Both grow as they absorb more defects

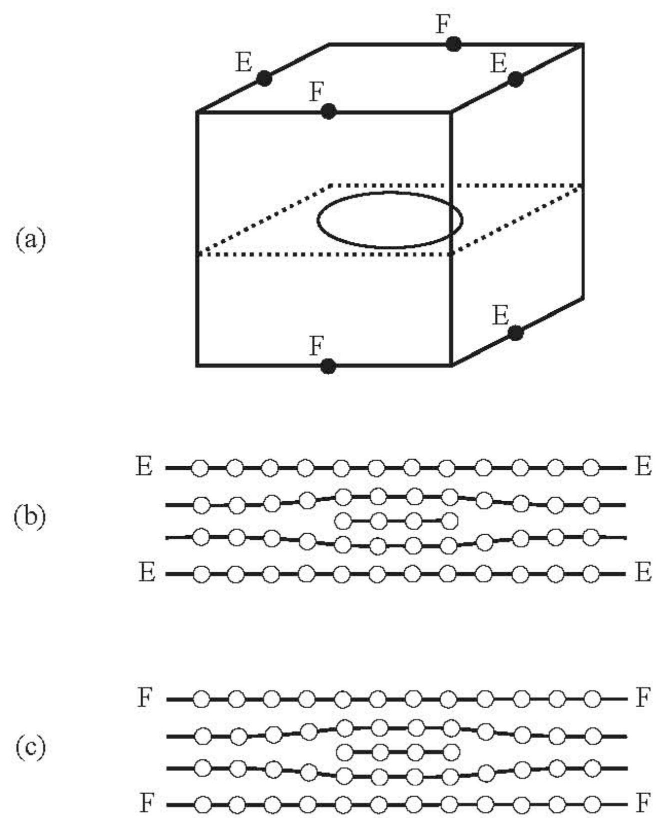


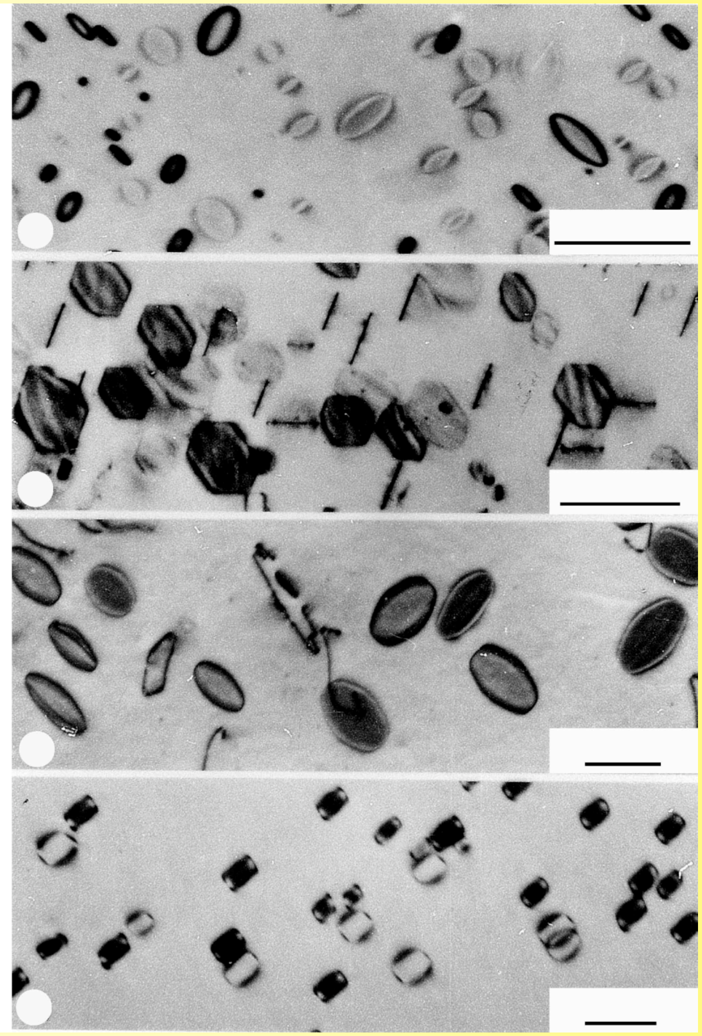


Source: T.R. Allen

Interstitials (or vacancies) can also cluster into discs

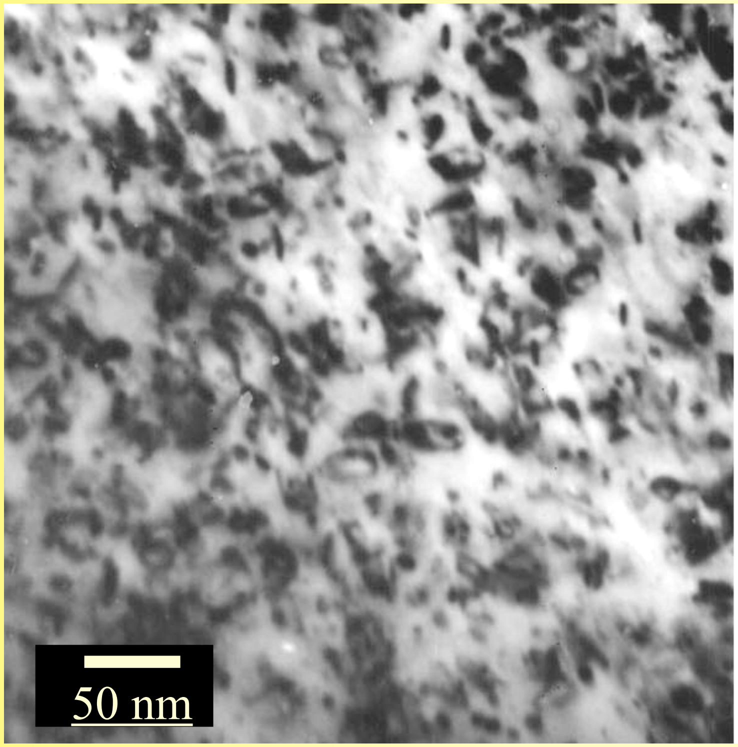
Faulted (Frank) Loop



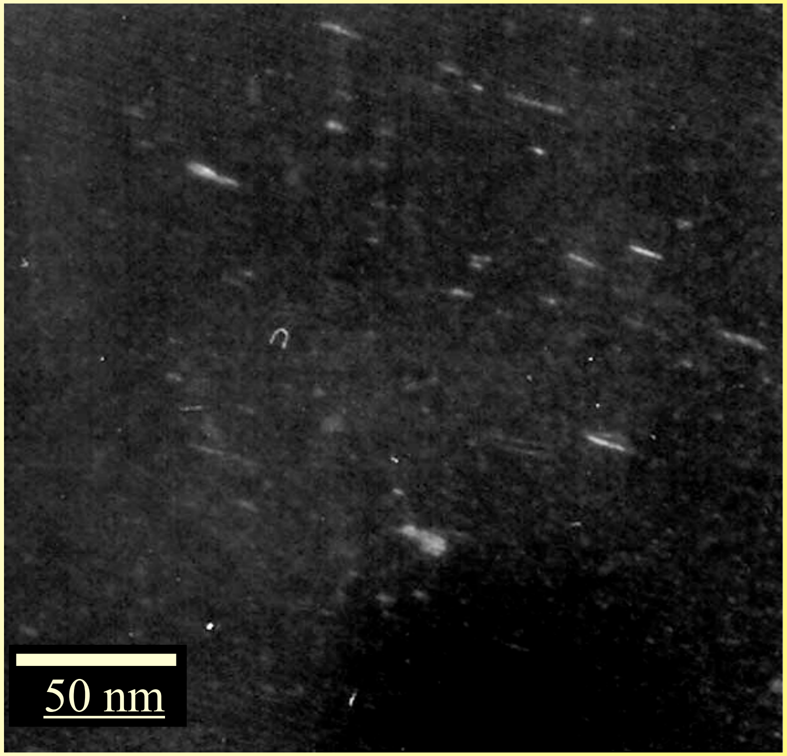


M. Kiritani, JNM 1994

Dislocation loop microstructure is observed using transmission electron microscopy



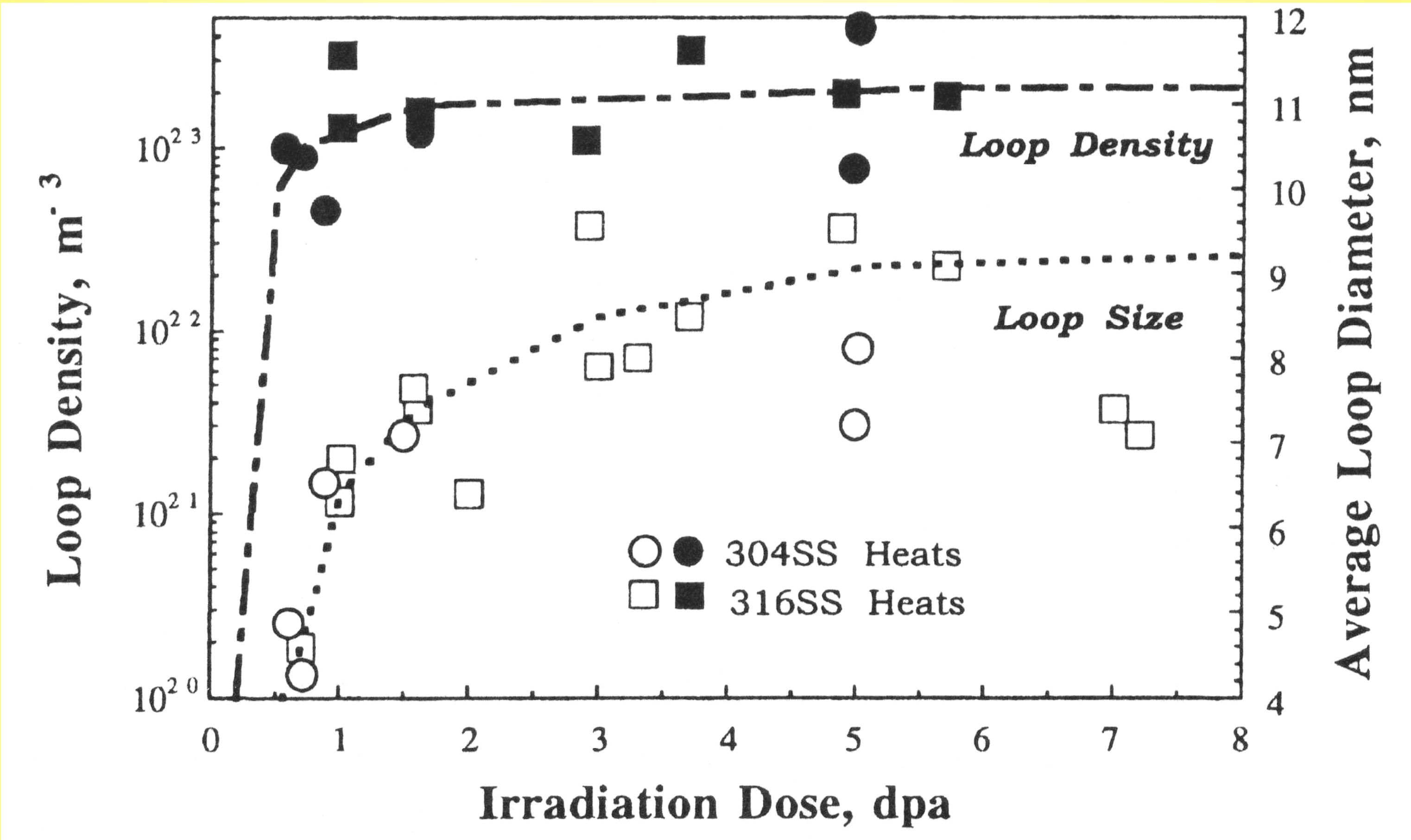
Bright Field



Dark Field

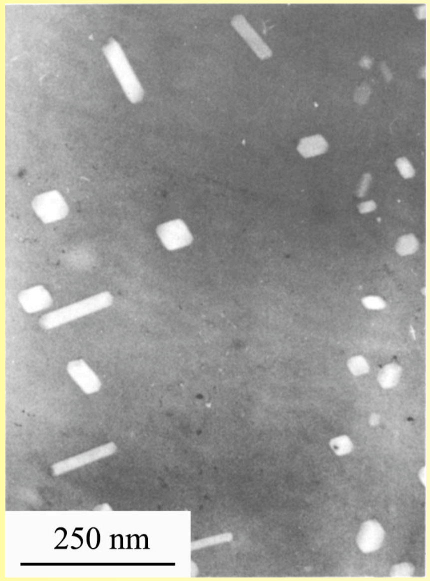
CP-304 SS irradiated to 0.55 dpa with protons at 360°C

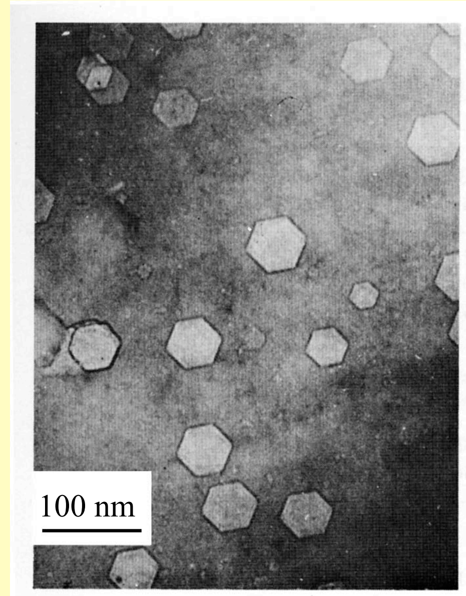
Behavior of Dislocation Loop Size and Number Density

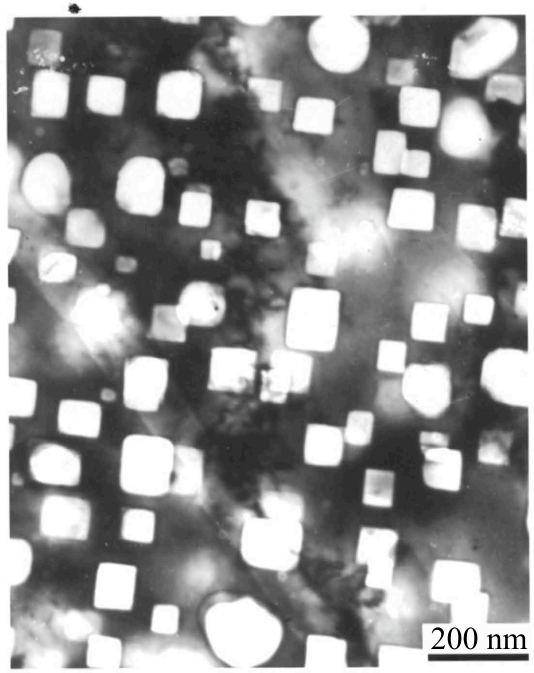


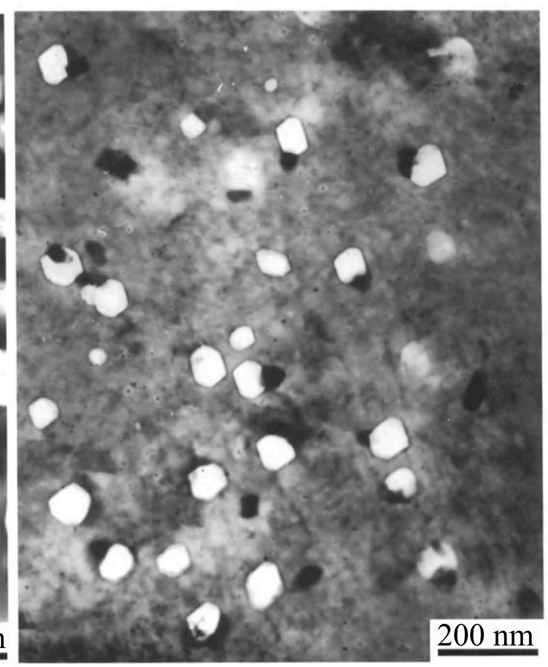
S. Bruemmer et al. JNM 274 (1999) 299.

Voids



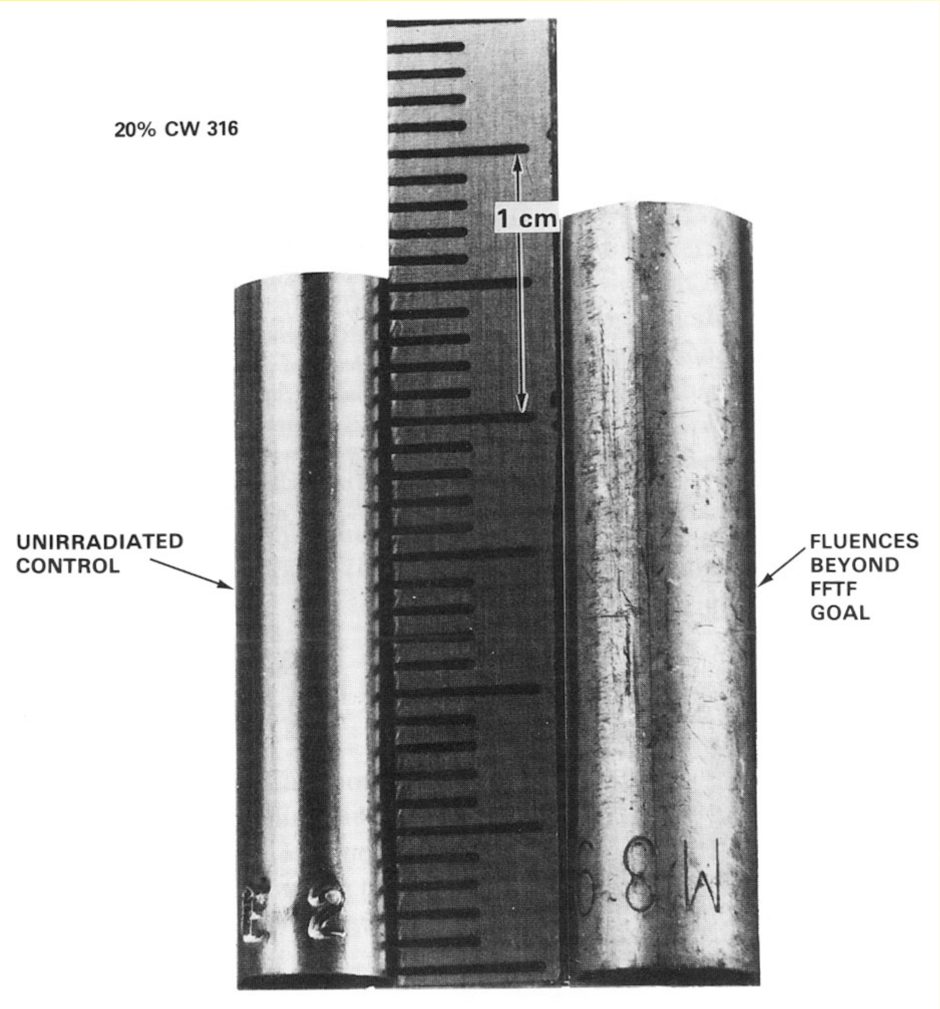


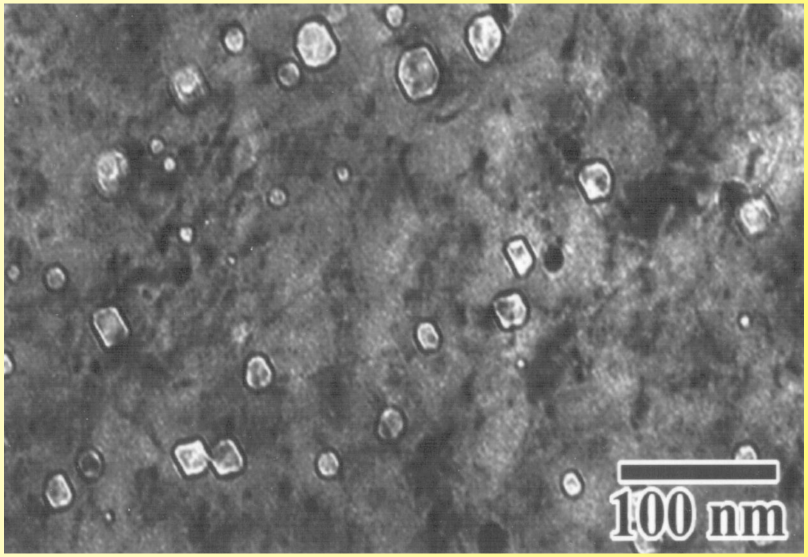




M. Jenkins, et al, 2001 and U. Adda, 1972

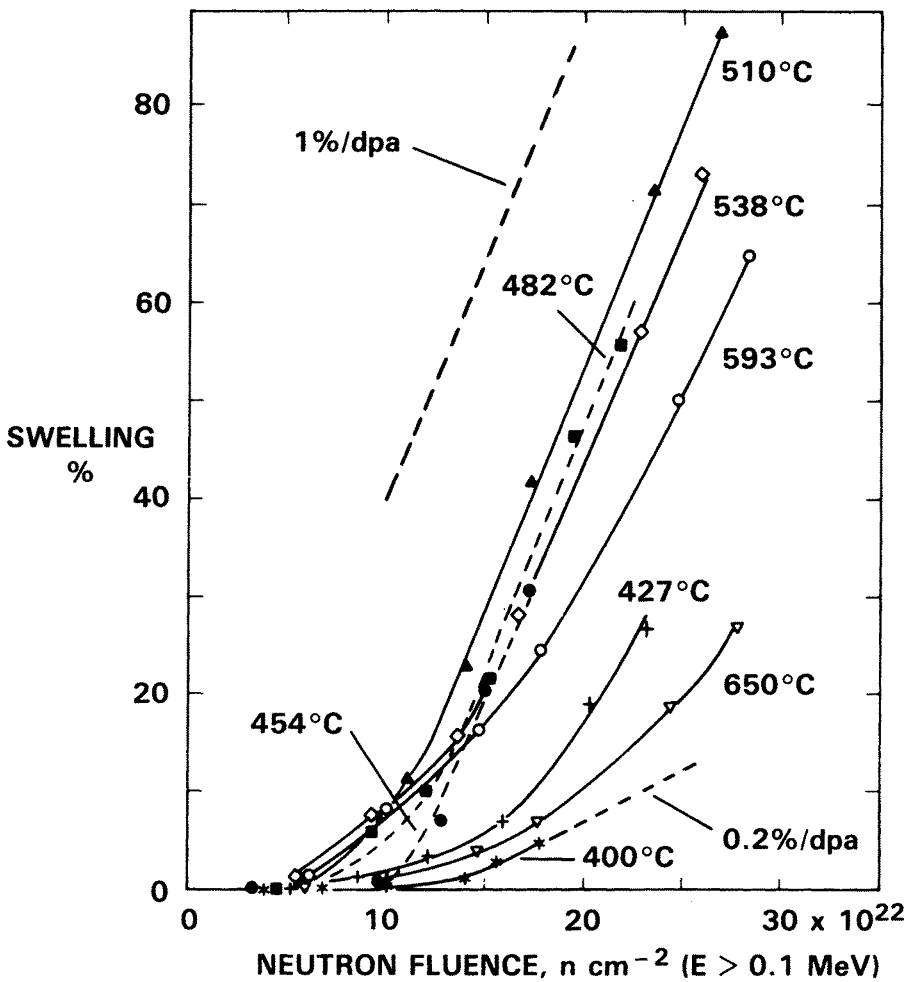
Swelling is readily observed in many steels under various reactor conditions





Straalsund, 1982, and F. Garner

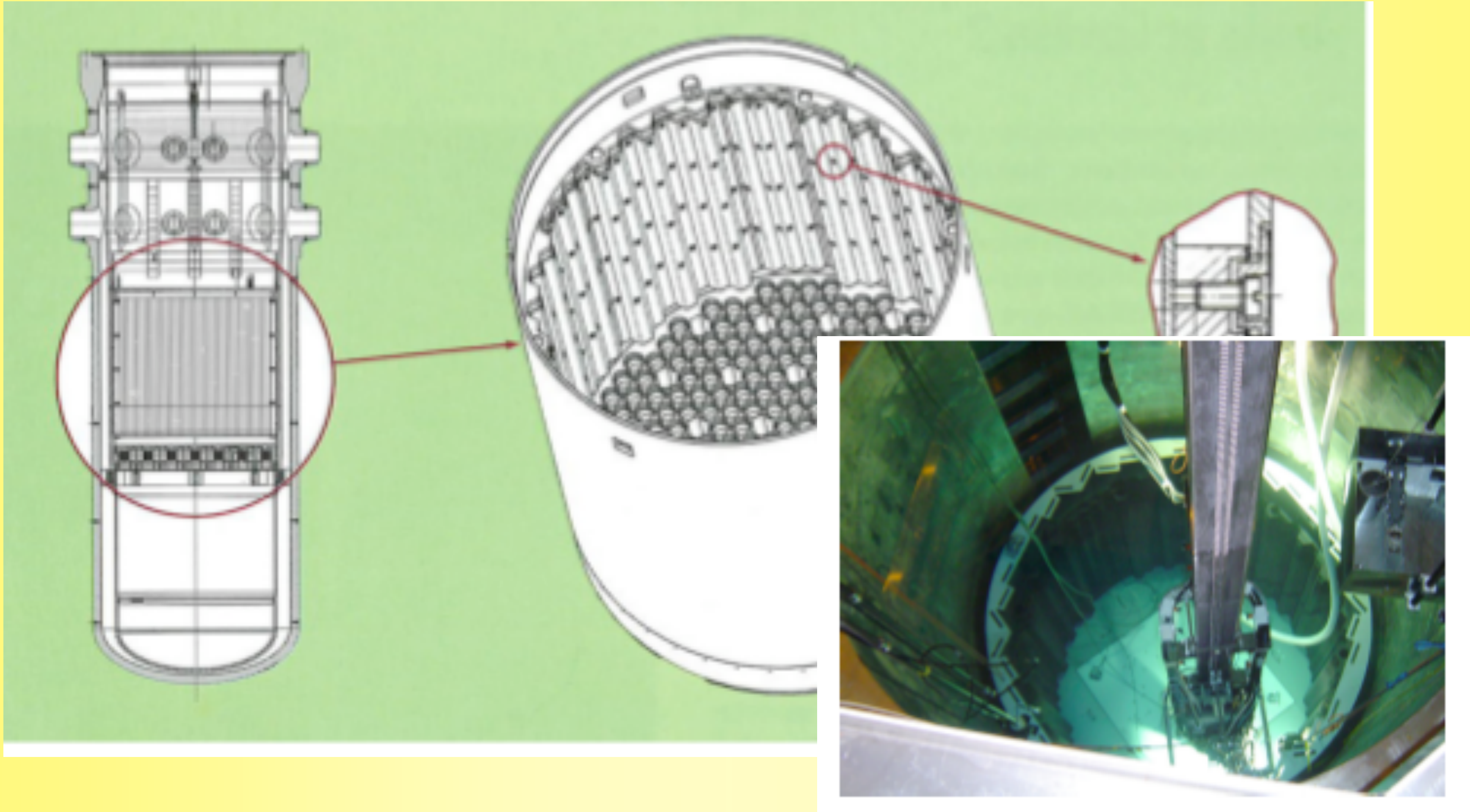
Swelling of 20% CW 316 stainless steel in EBR-II (Garner and Gelles, 1990)



- Swelling occurs above temperatures above <u>~300ºC</u>.
- The eventual swelling rate of 316 at all temperatures is ~1%/dpa.
- The temperature dependence lies only in the duration of the transient regime.
- The transient regime is <u>very</u> sensitive to any material or environmental variable.

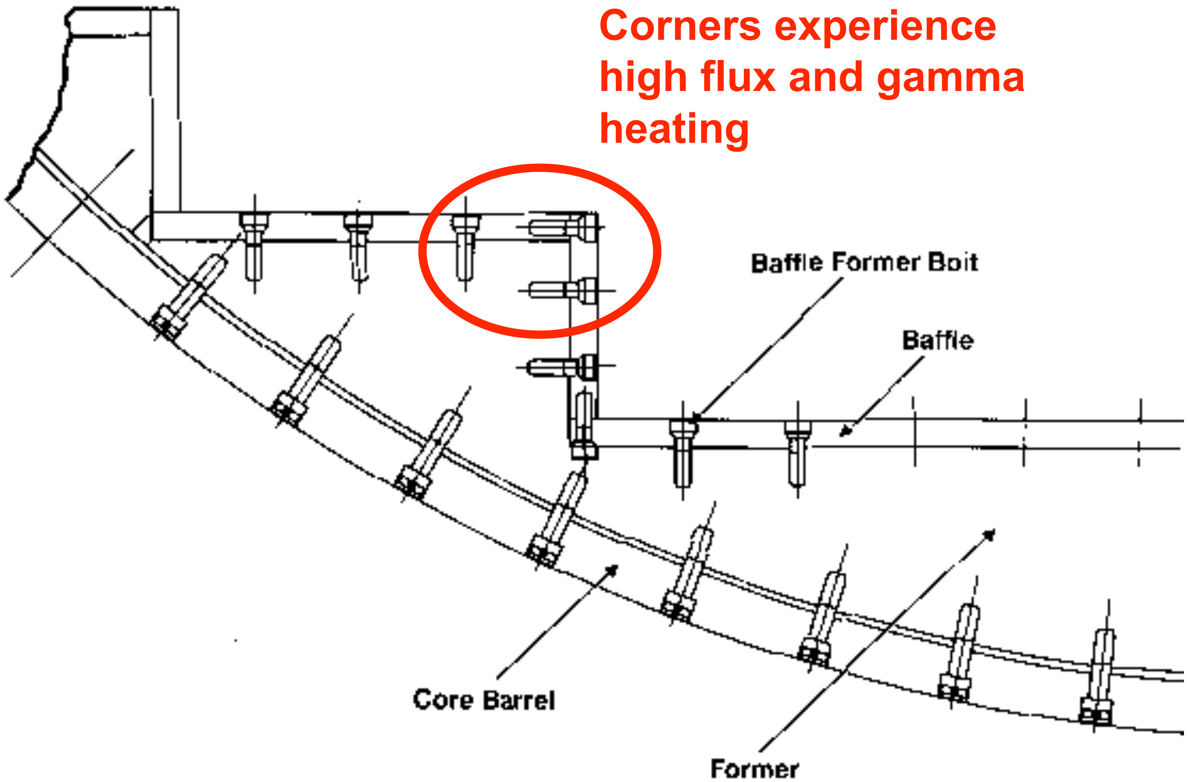
Source: F. Garner

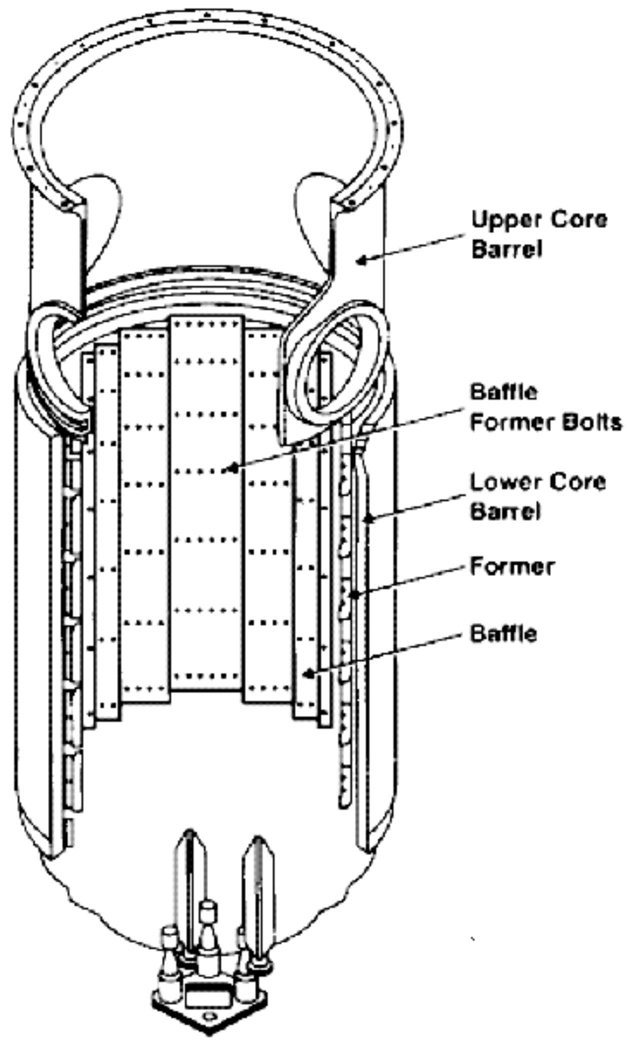
Baffle bolts experience some of the highest fluences and temperatures in a PWR core



Baffle bolts experience some of the highest fluences and temperatures in a PWR core

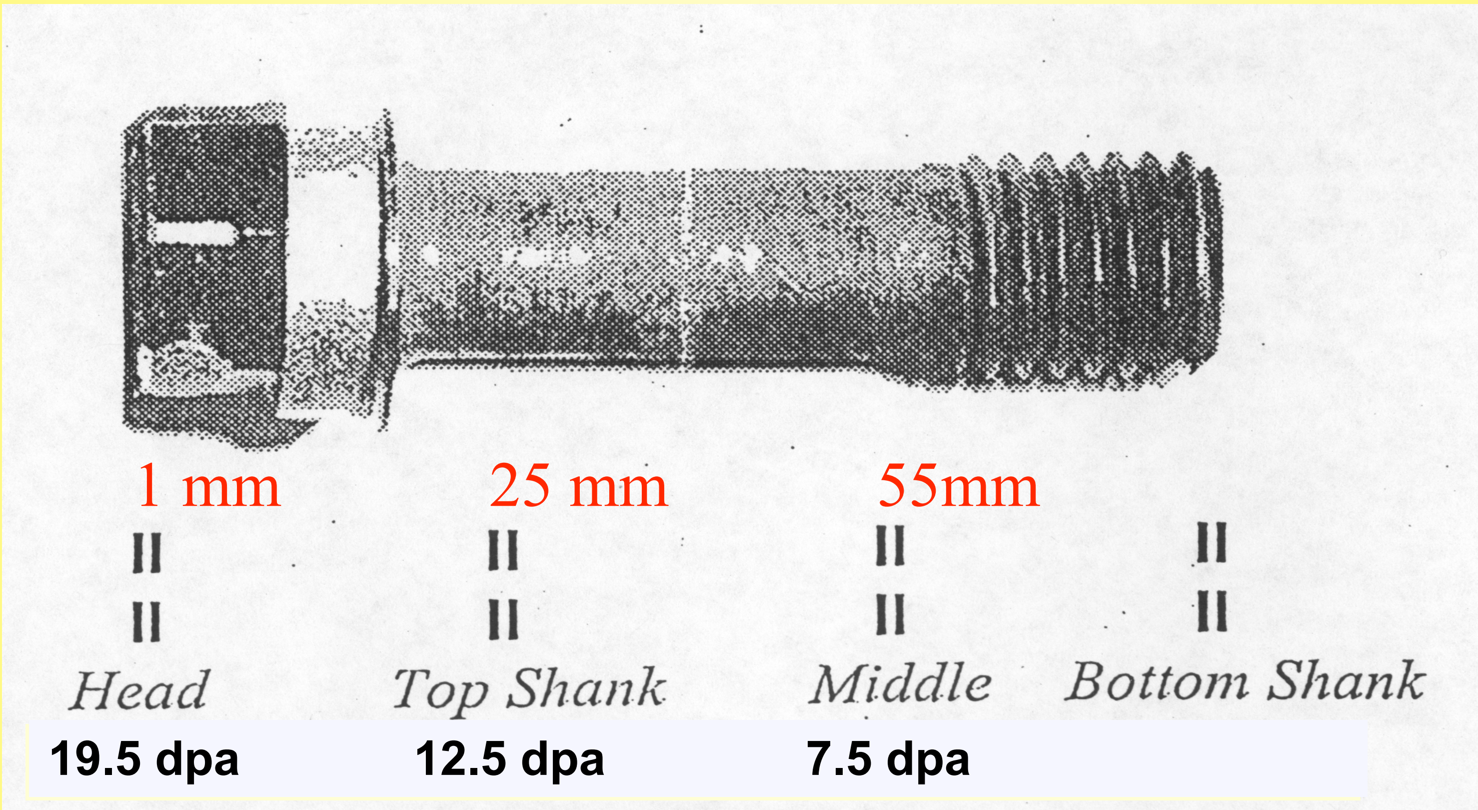
Corners experience high flux and gamma heating





Cutting diagram for 15% cold-worked 316 baffle bolt after 20 years in a PWR

Edwards, Garner, Oliver and Bruemmer, 2003



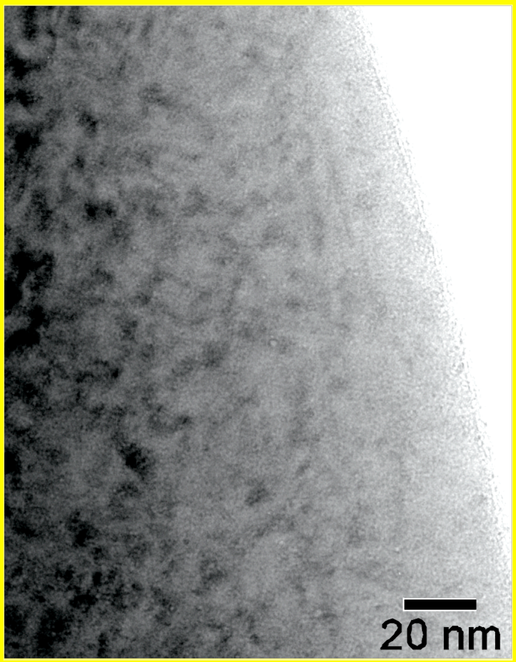
~320°C ~345°C ~330°C ~324ºC

Source: S.M. Bruemmer, F. Garner

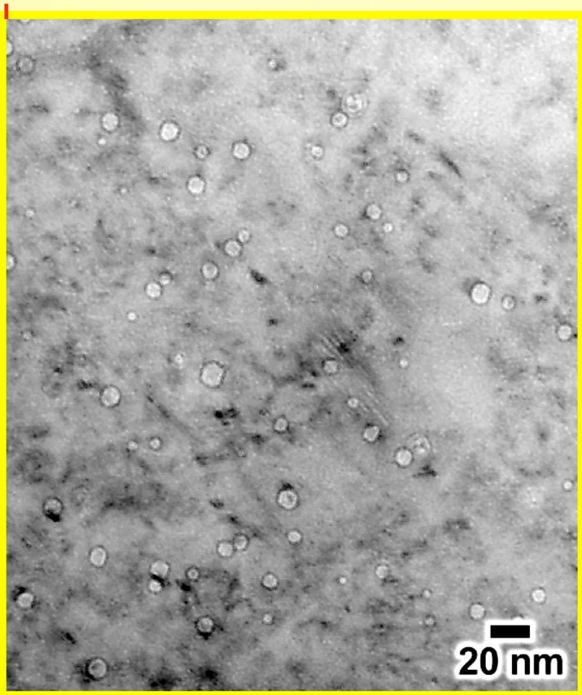
Swelling and helium content observed in CW 316SS baffle-former bolt

Edwards, Garner, Oliver and Bruemmer, 2003

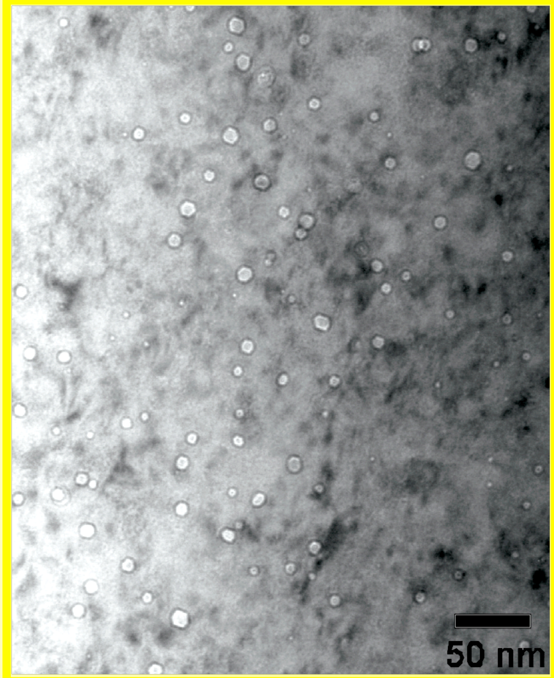
<.0.01%, 71 appm Helium | Both at ~0.2% swelling , 53 and 49 appm Helium



Bolt Head, 1 mm
19.5 dpa, ~320°C



Top Shank, 25 mm
12.5 dpa, ~343°C

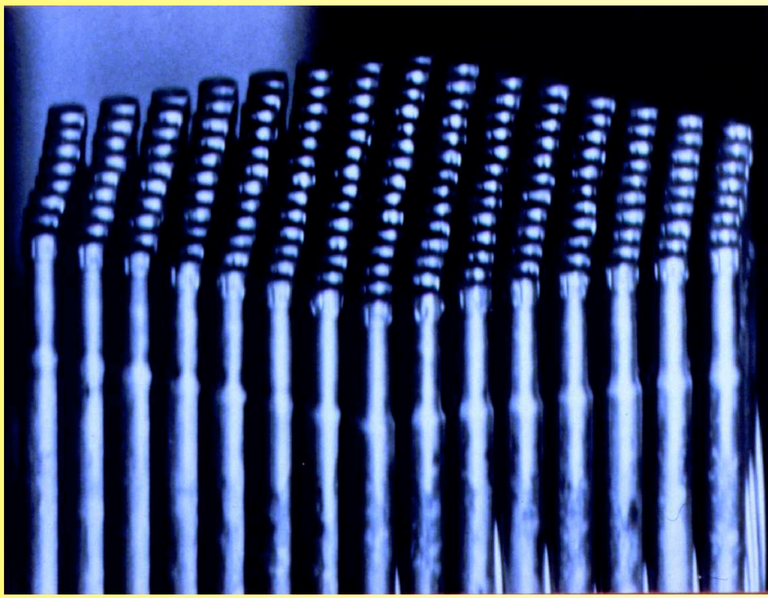


Near Threads, 55 mm
7 .5 dpa, ~333°C

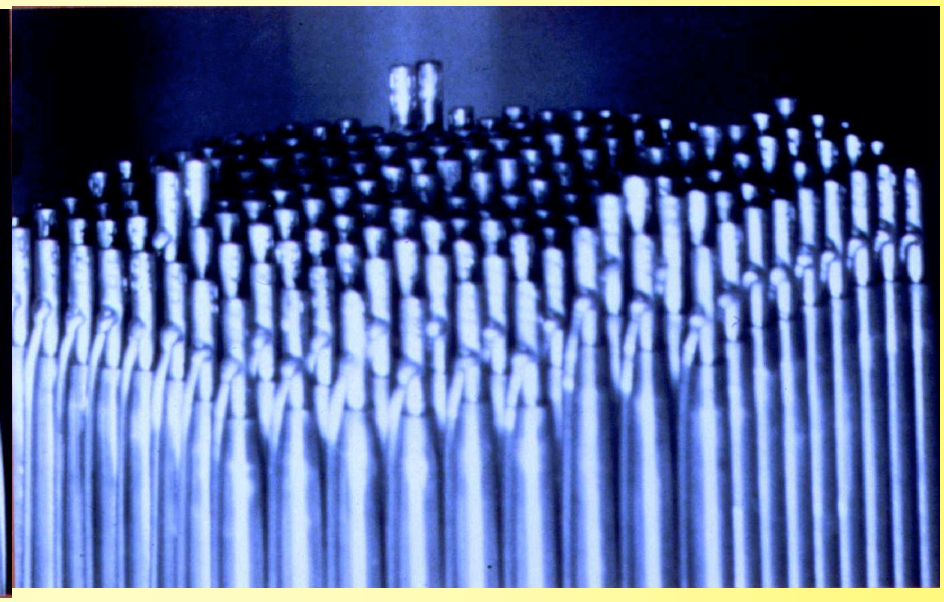
Source: S.M. Bruemmer, F. Garner

Swelling can create tolerance problems

FFTF Fuel Pin Bundles



HT-9, no swelling



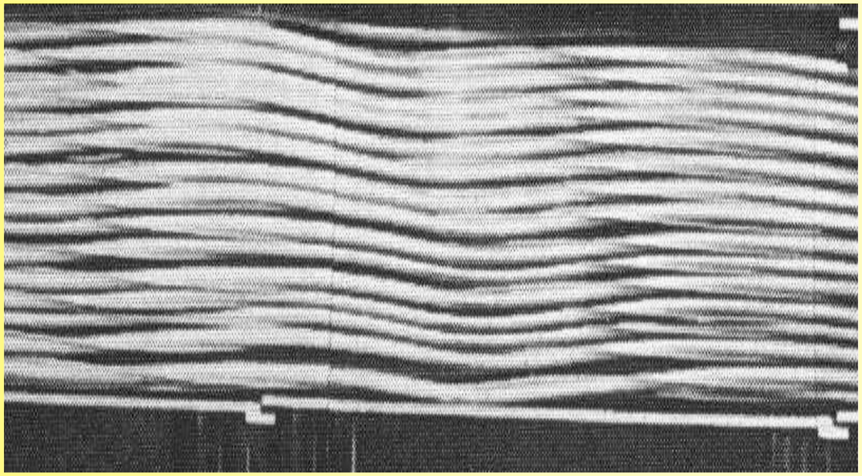
316-Ti stainless, swelling

Source: F. Garner

Swelling behavior under constrained conditions

- Swelling strains are isotropically distributed in the absence of constraint.
- In presence of constraint the swelling strain is directed toward unconstrained or less-constrained directions.
- Constraints can be externally applied or arise internally from gradients in swelling.
- "Thick vs. Thin" data

"Thin" implies no gradients in temperature, dpa rate or stress.

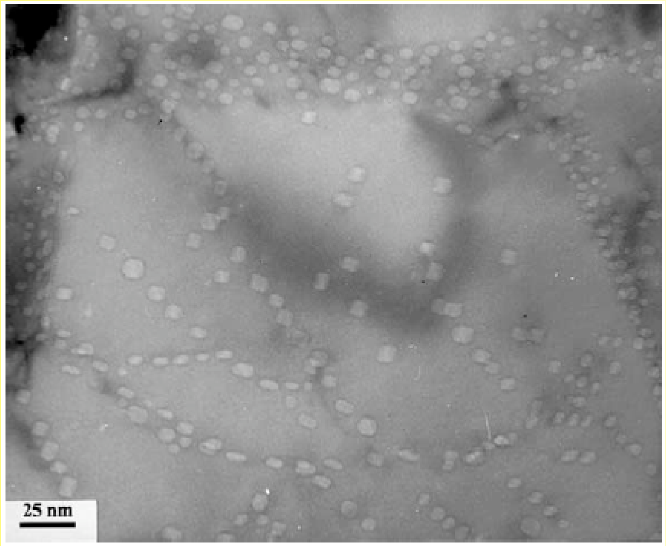


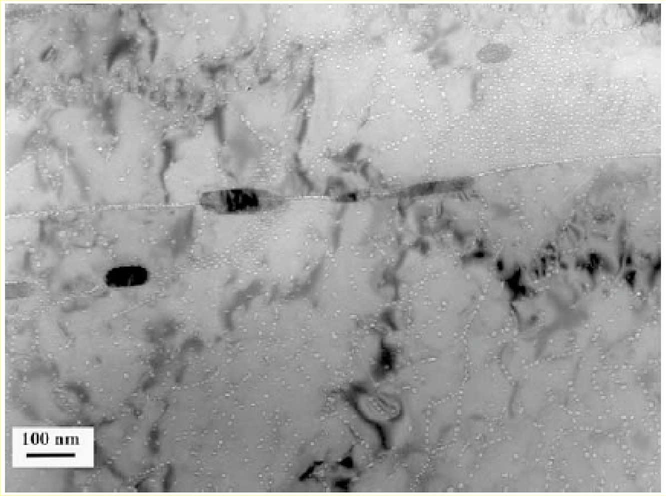
Stresses generated by swelling or swelling gradients will never exceed the yield stress.

Source: F. Garner

Bubble formation and growth

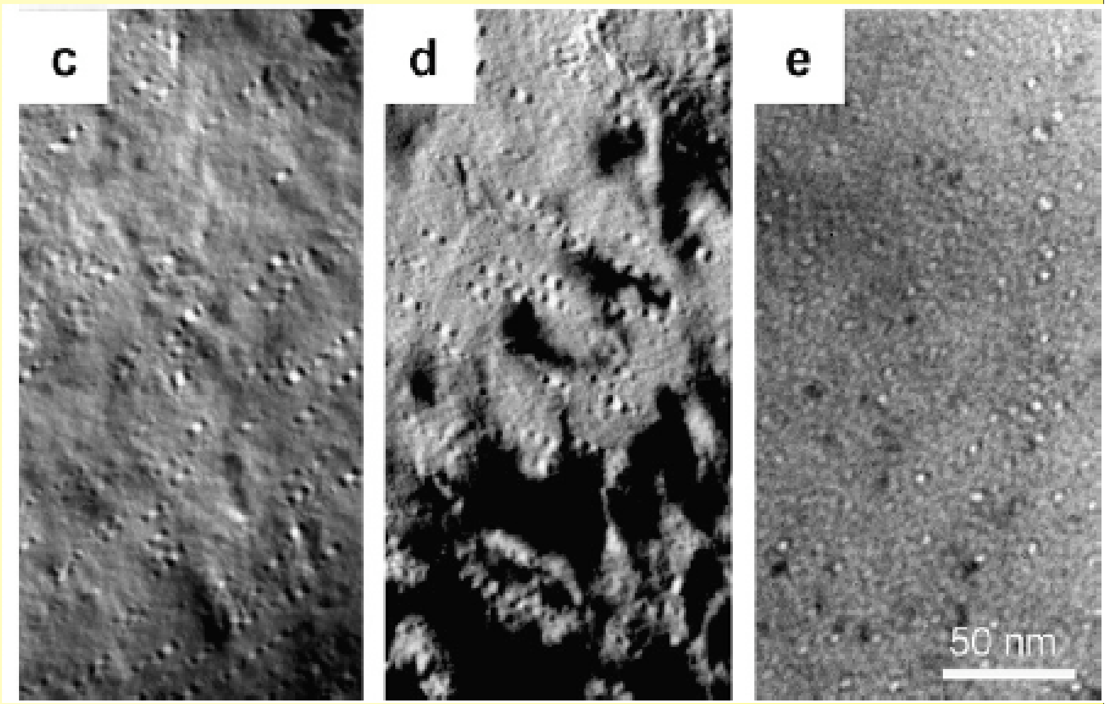
He in EM10 at 550°C





J. Henry et al., JNM 318 (2003) 249.

He in T91 at 450°C

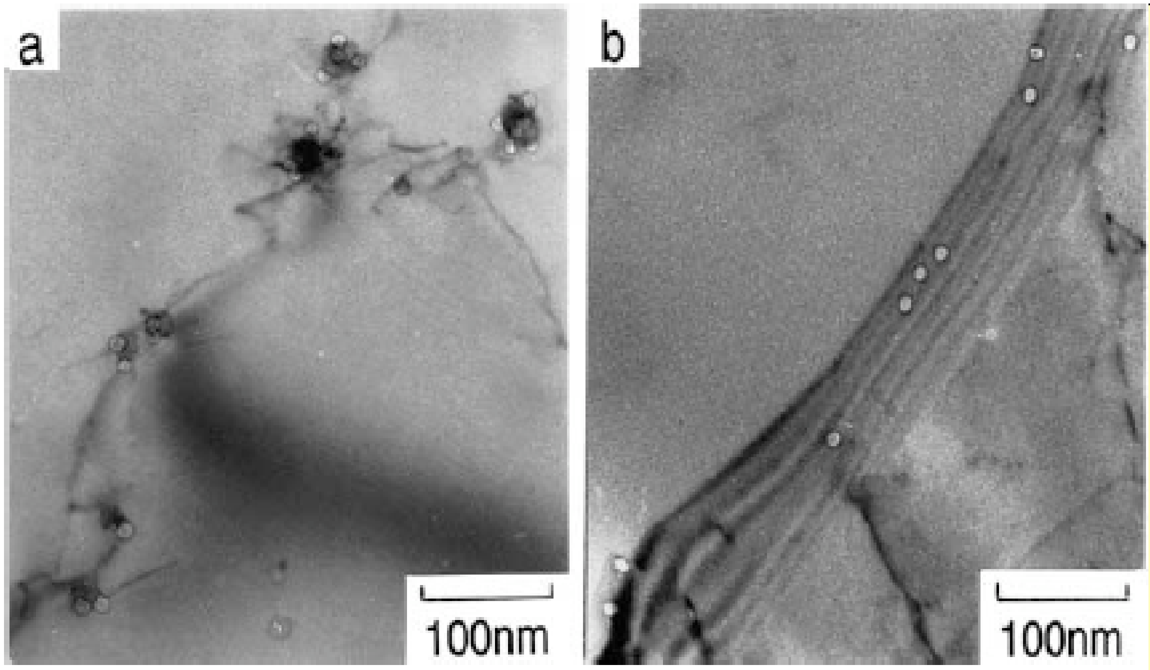


Z. Jiao, N. Ham and G. S. Was, JNM 367-370 (2007) 440.

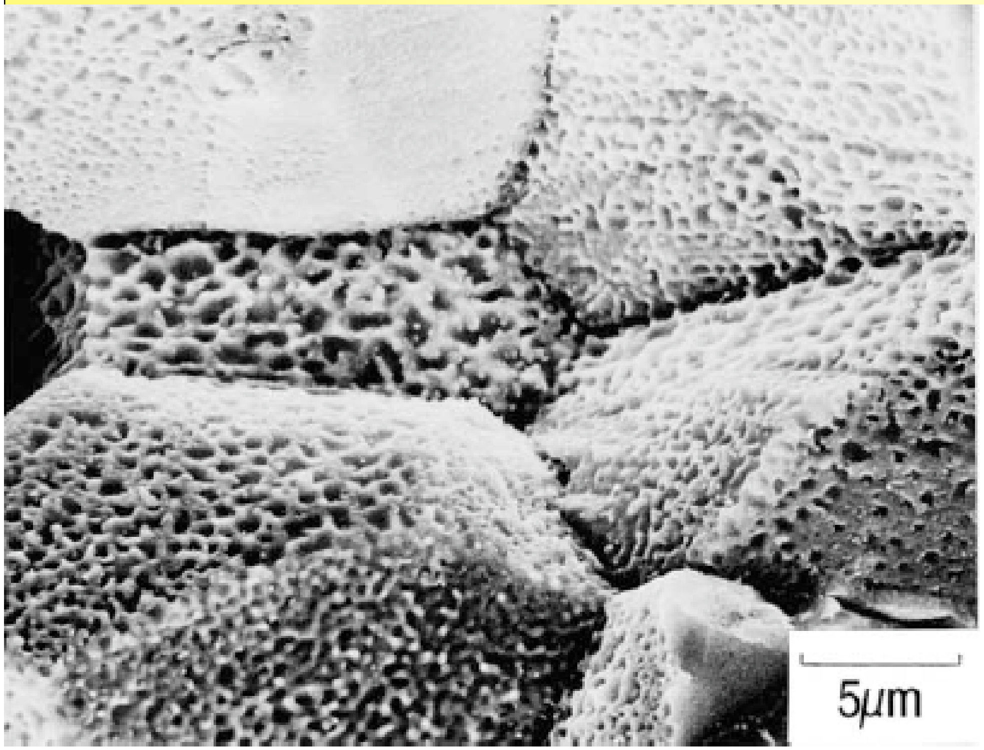
Bubble formation and growth

He bubbles need space to grow. Space comes from addition of vacancies. The larger the He bubble, the more space is needed per He atom to keep the bubble in mechanical equilibrium.

Bubble Radius	m_v/m_{He}
1 nm	2
10 nm	6
100 nm	27

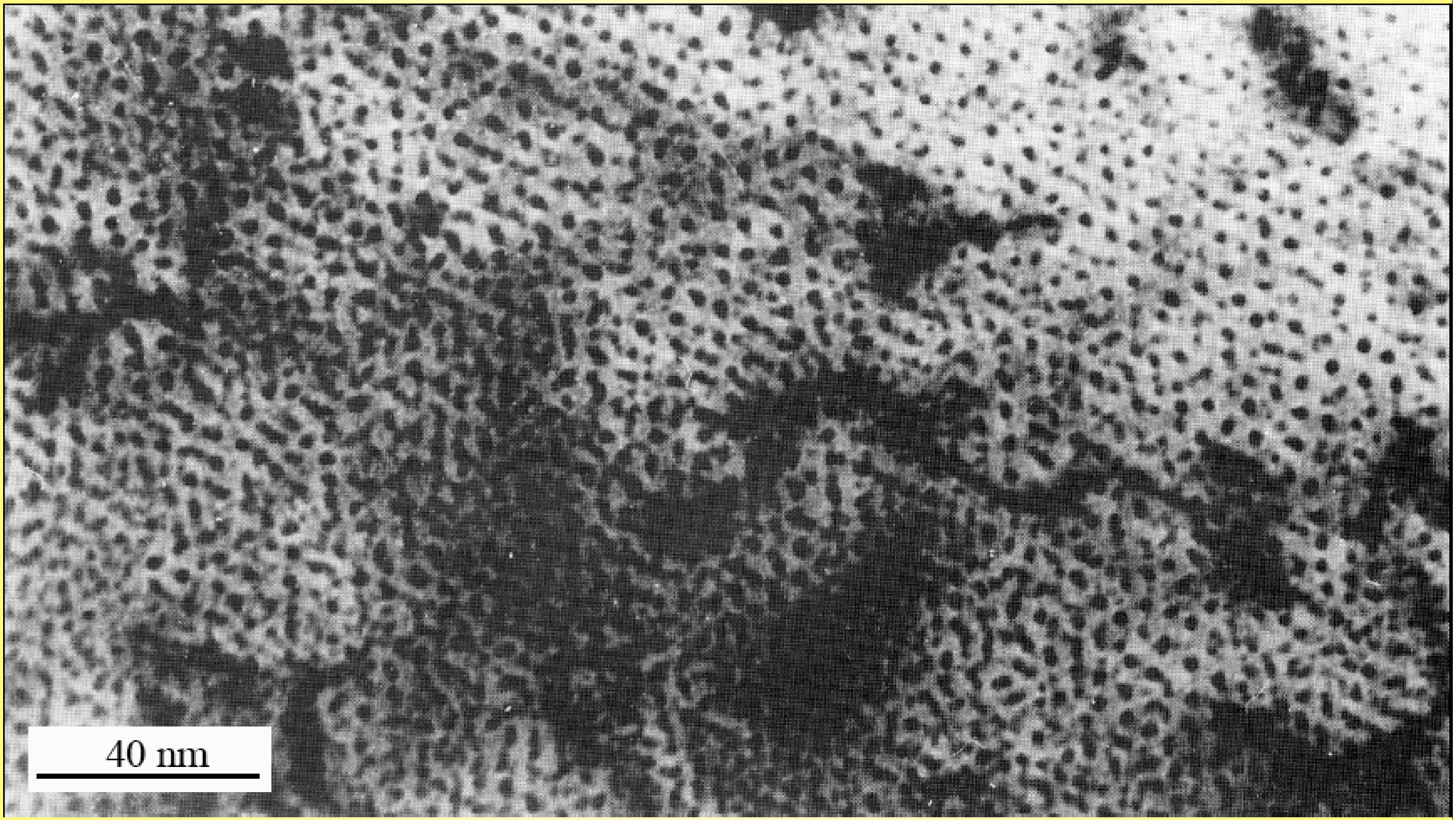


He bubble microstructure in Fe-25Ni-15Cr alloys (top) and in Fe-15Ni-15Cr (bottom)



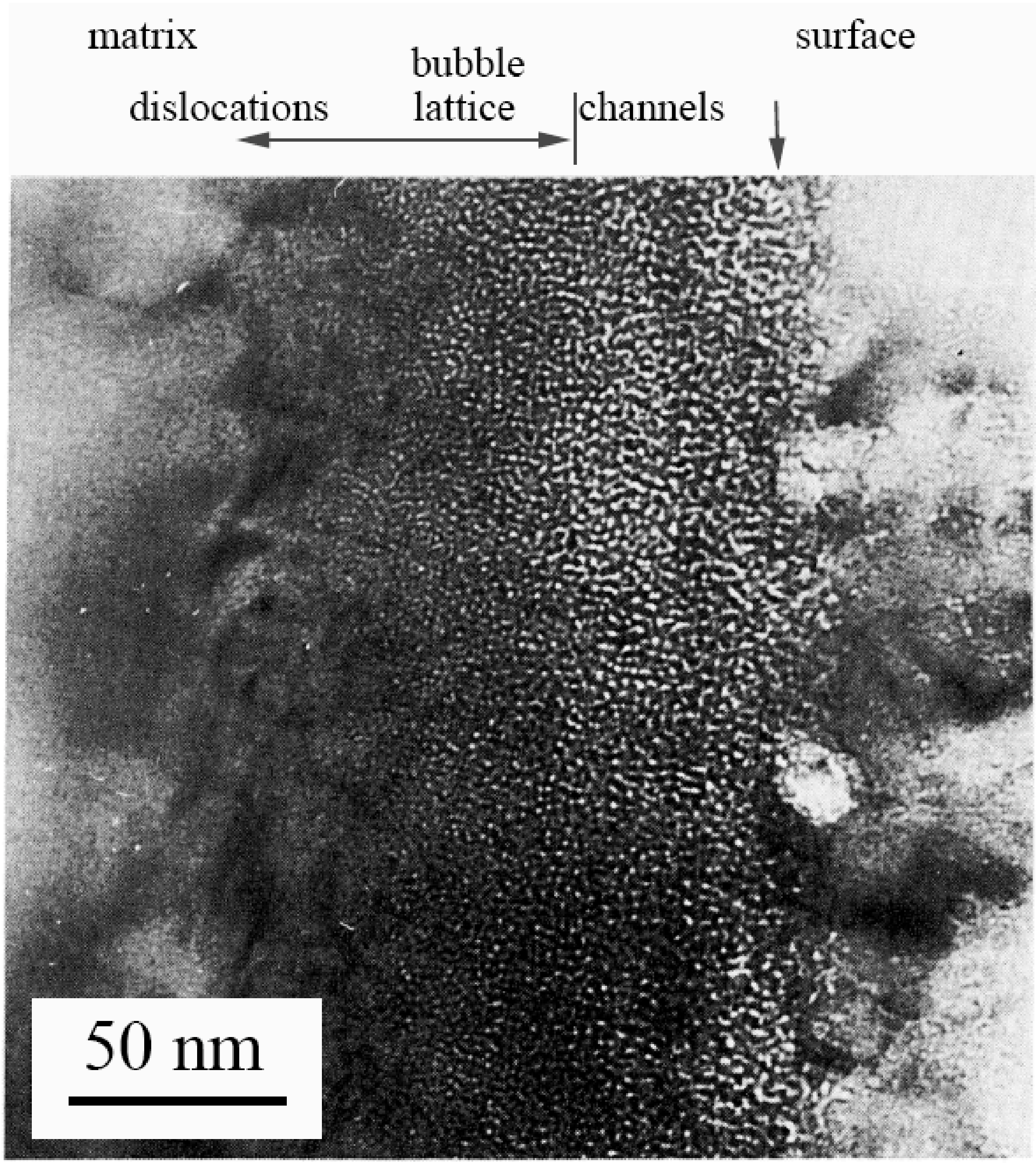
N. Yamamoto et al., JNM 329-333 (2004) 993.

He gas bubble superlattice formed in Mo by He implantation at 500°C



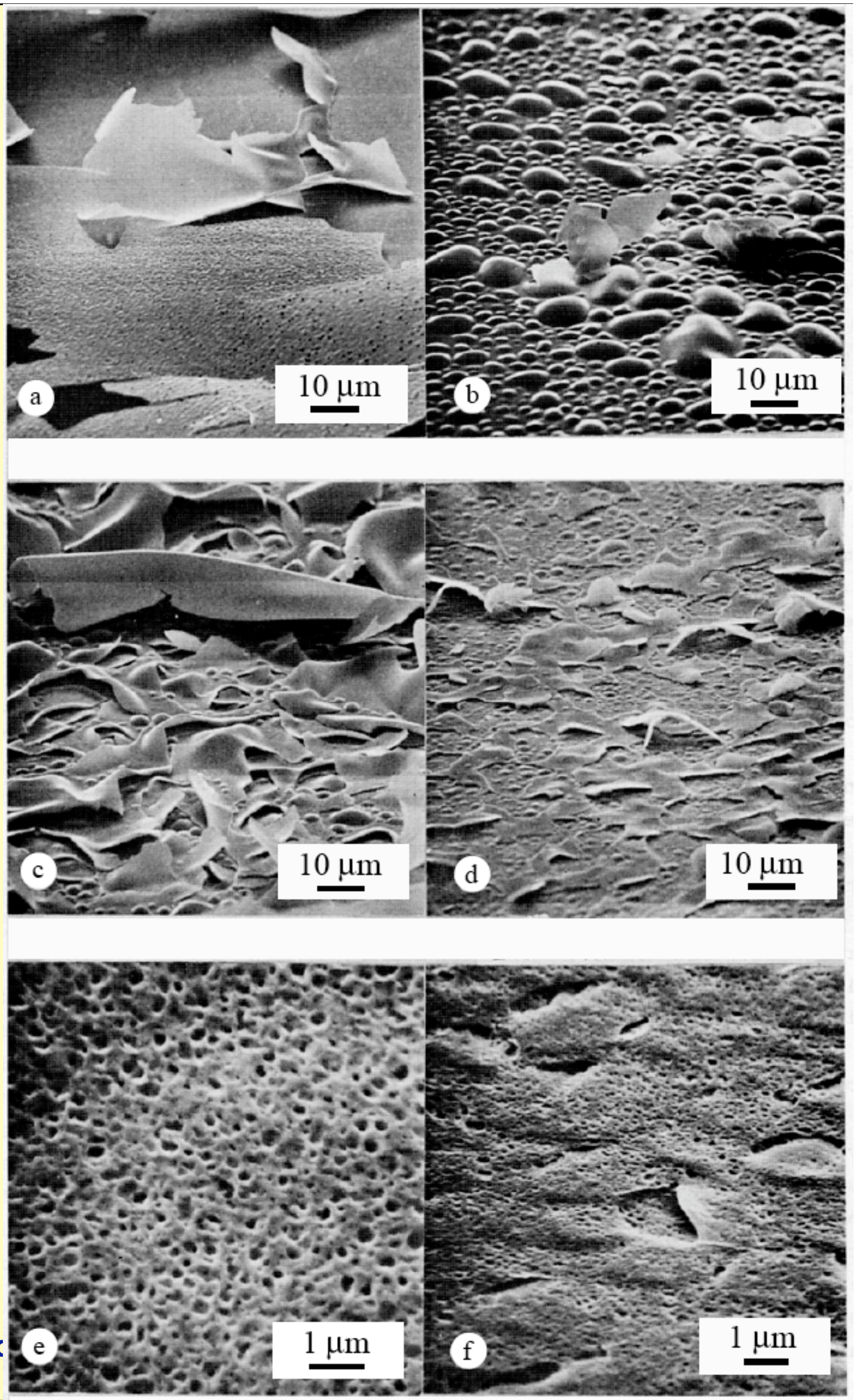
N.M. Ghoniem, et al. Comp. Aided Mater Des 8 (2002) 1.

He-implanted nickel



H. Ullmaier, Rad. Eff. 78 (1983) 1.

Surface of nickel sample following implantation of different doses of helium to shallow depths



R. Behrisch et al. Proc. 9th Symp. Fusion Technol. Pergamon, NY, 1976, p. 531.

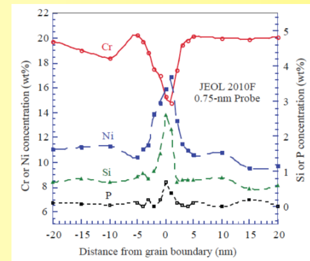
Fundamentals of Radiation Damage

Mechanical Effects of Radiation Damage

- Radiation hardening and localized deformation
- Fracture and embrittlement
- Irradiation creep
- Irradiation assisted stress corrosion cracking (IASCC)

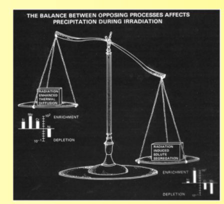
Major forms of radiation damage in reactor structural materials

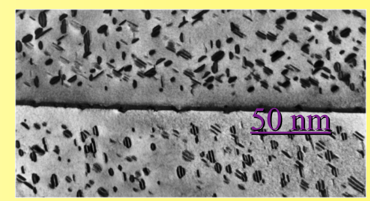
- Radiation induced segregation (<0.4 T_M, >0.1 dpa)



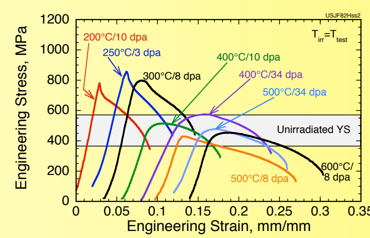
- Volumetric swelling from voids (0.3-0.6 T_M, >10 dpa) and high temperature He embrittlement (>0.5 T_M, >10 dpa)

- Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)





- Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)

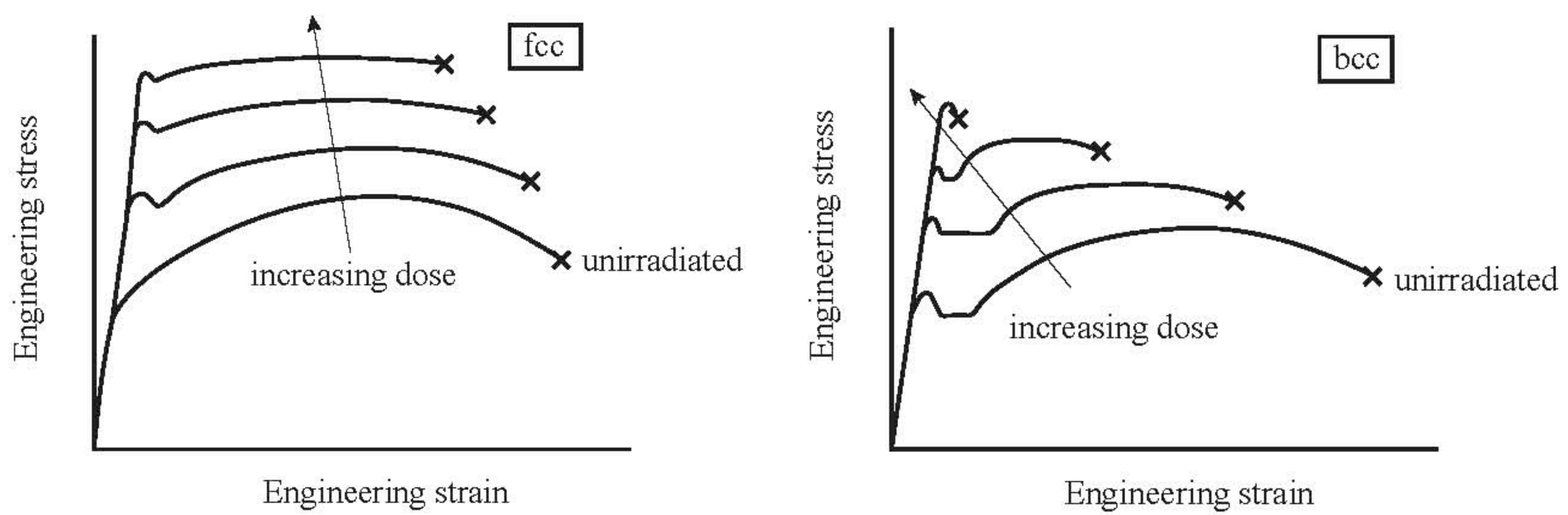


- Irradiation creep (<0.45 T_M, >10 dpa)

S. Zinkle

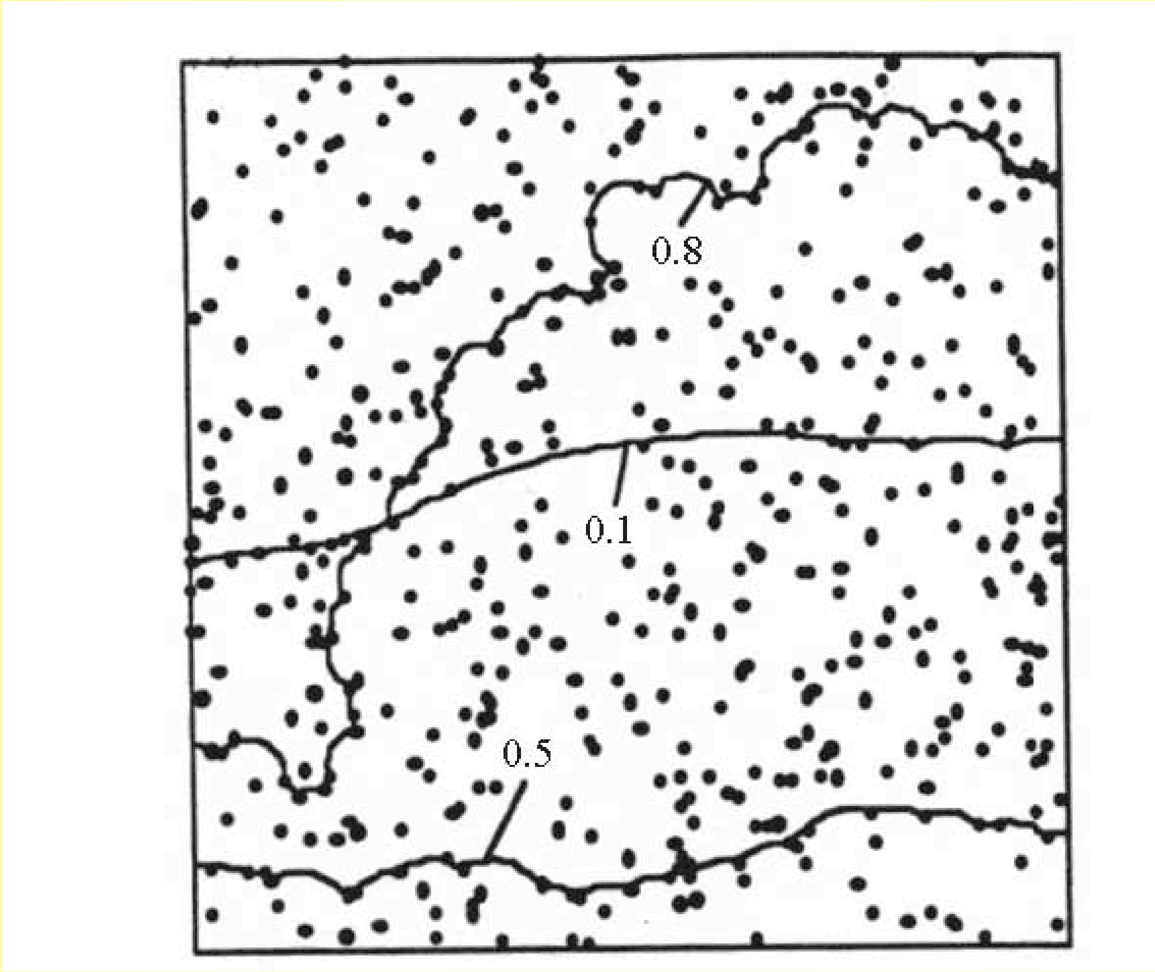
Irradiation-induced defects and microstructure influence stress-strain behavior

fcc bcc



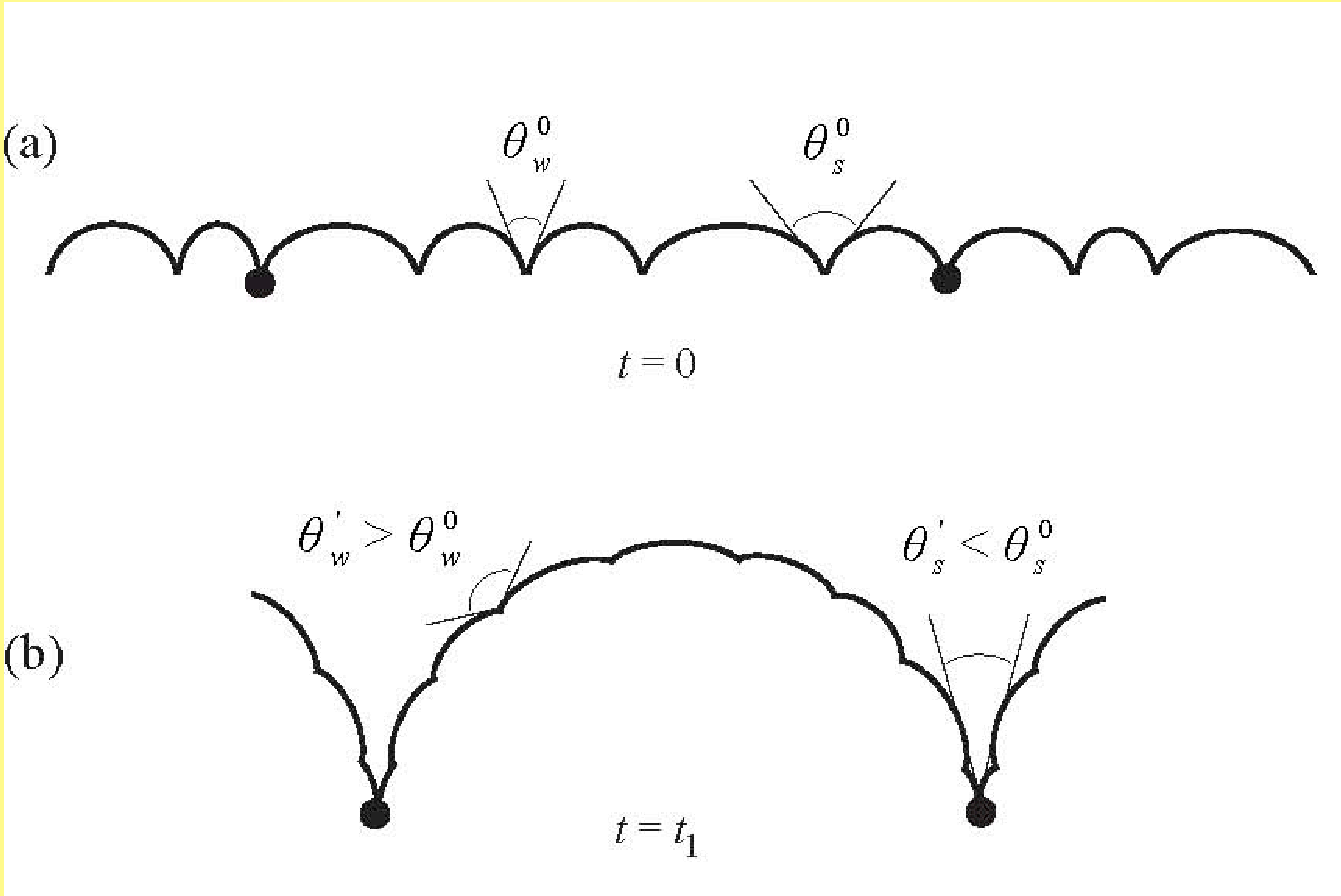
G.S. Was, Radiation Materials Science, 2007

Hardening is caused by dislocations trying to move through a field of radiation-produced obstacles



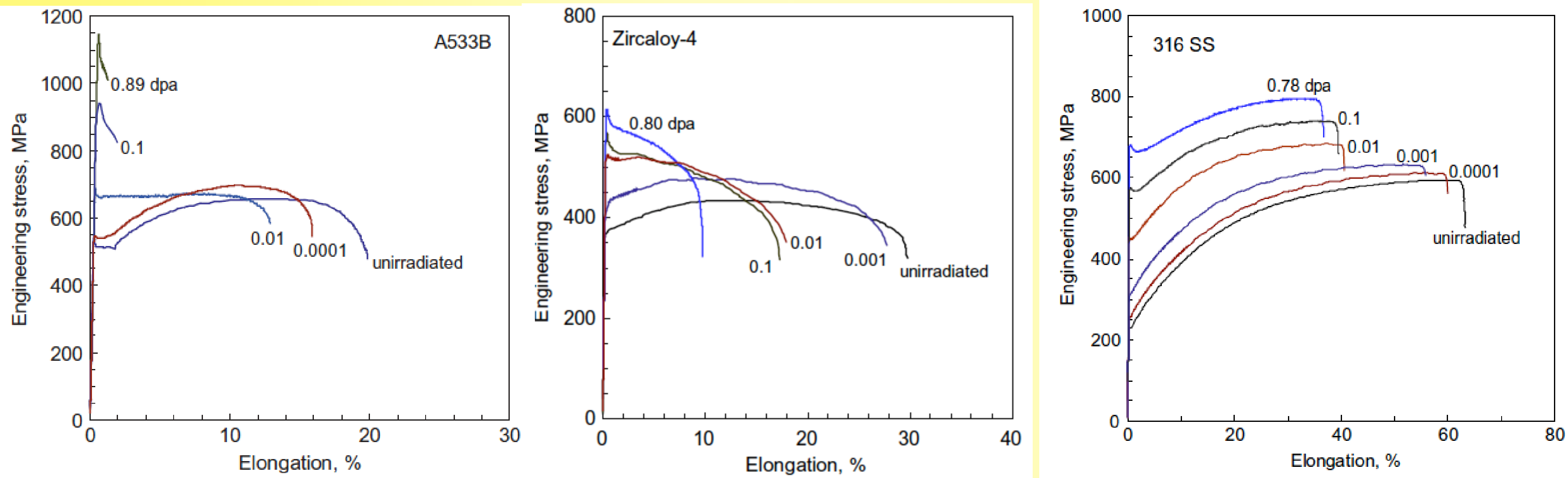
U.F. Kocks, 1969

Dislocations eventually break free

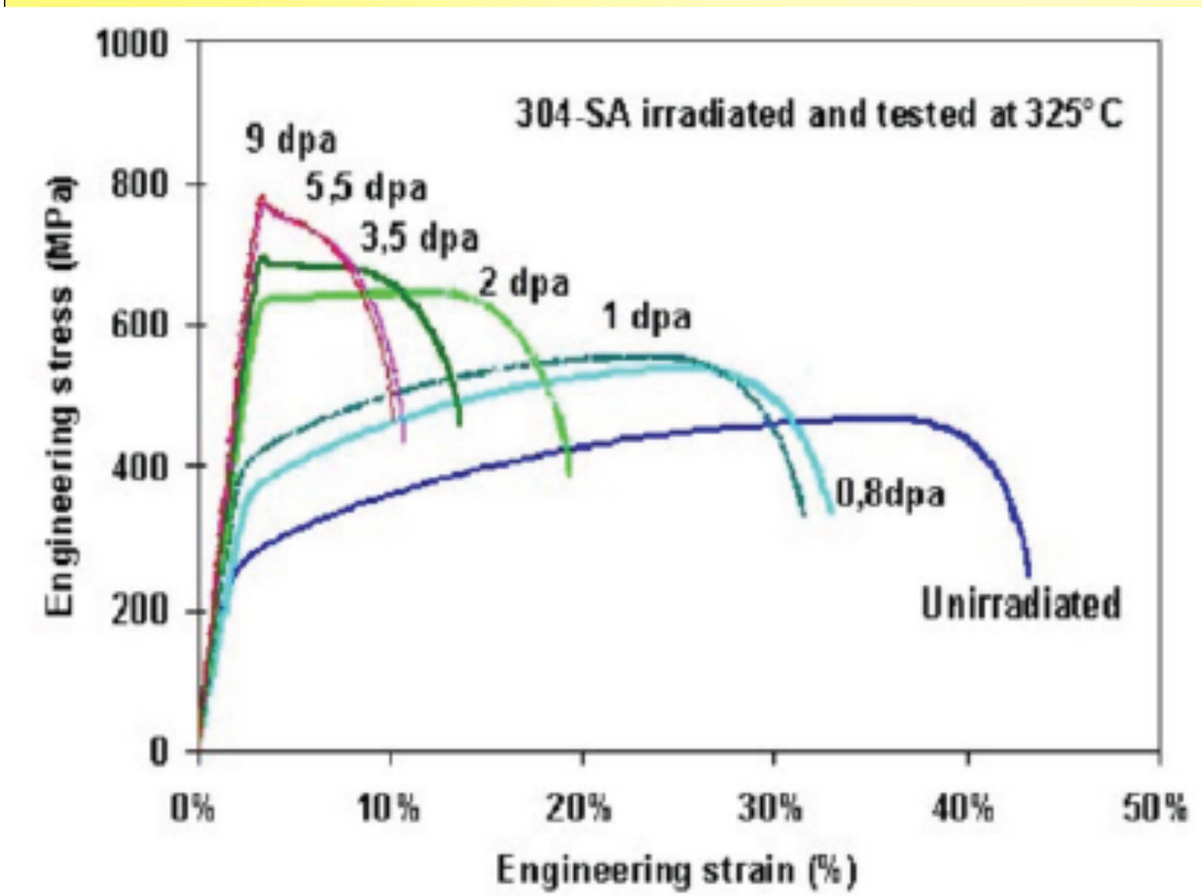


G.S. Was, Radiation Materials Science, 2007

Radiation hardening is observed in many classes of alloys

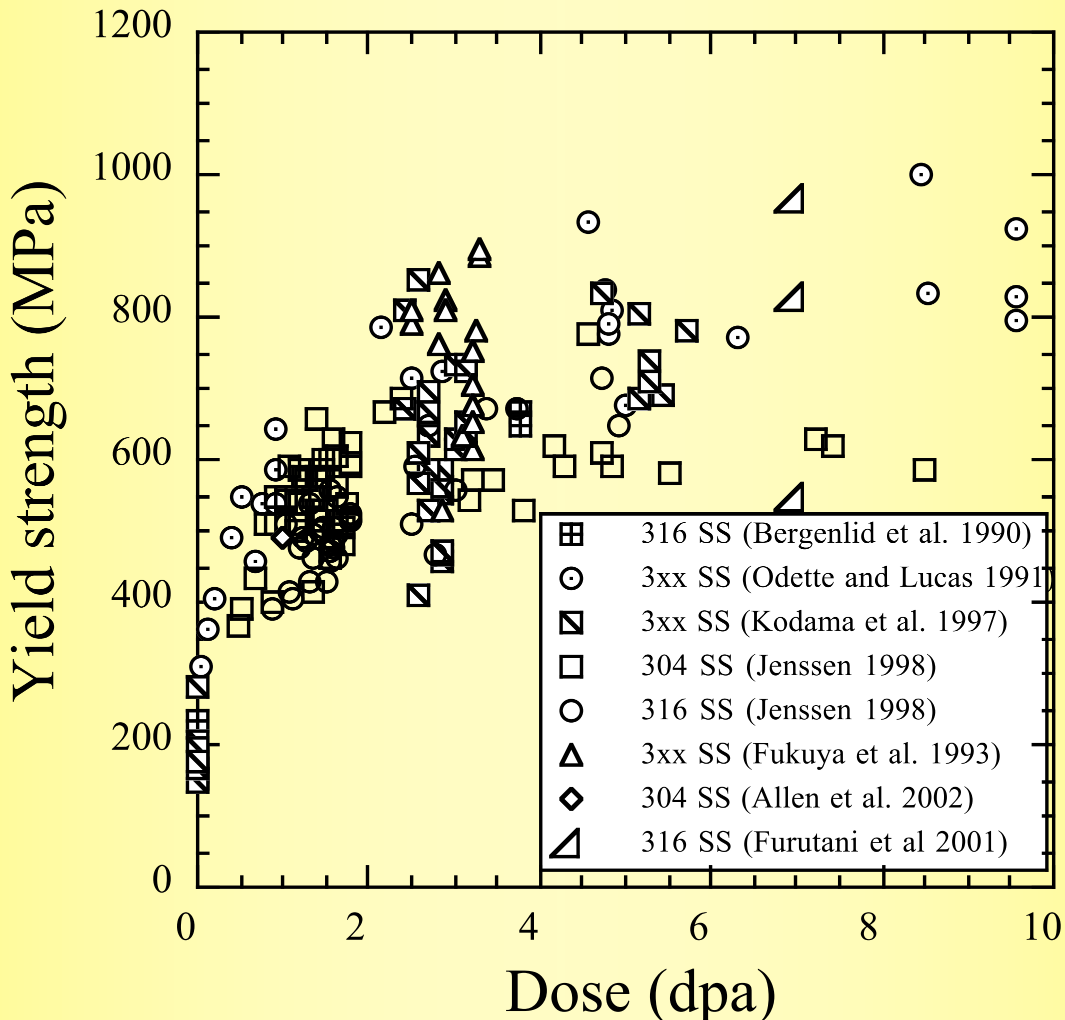


Radiation hardening is observed in many classes of materials



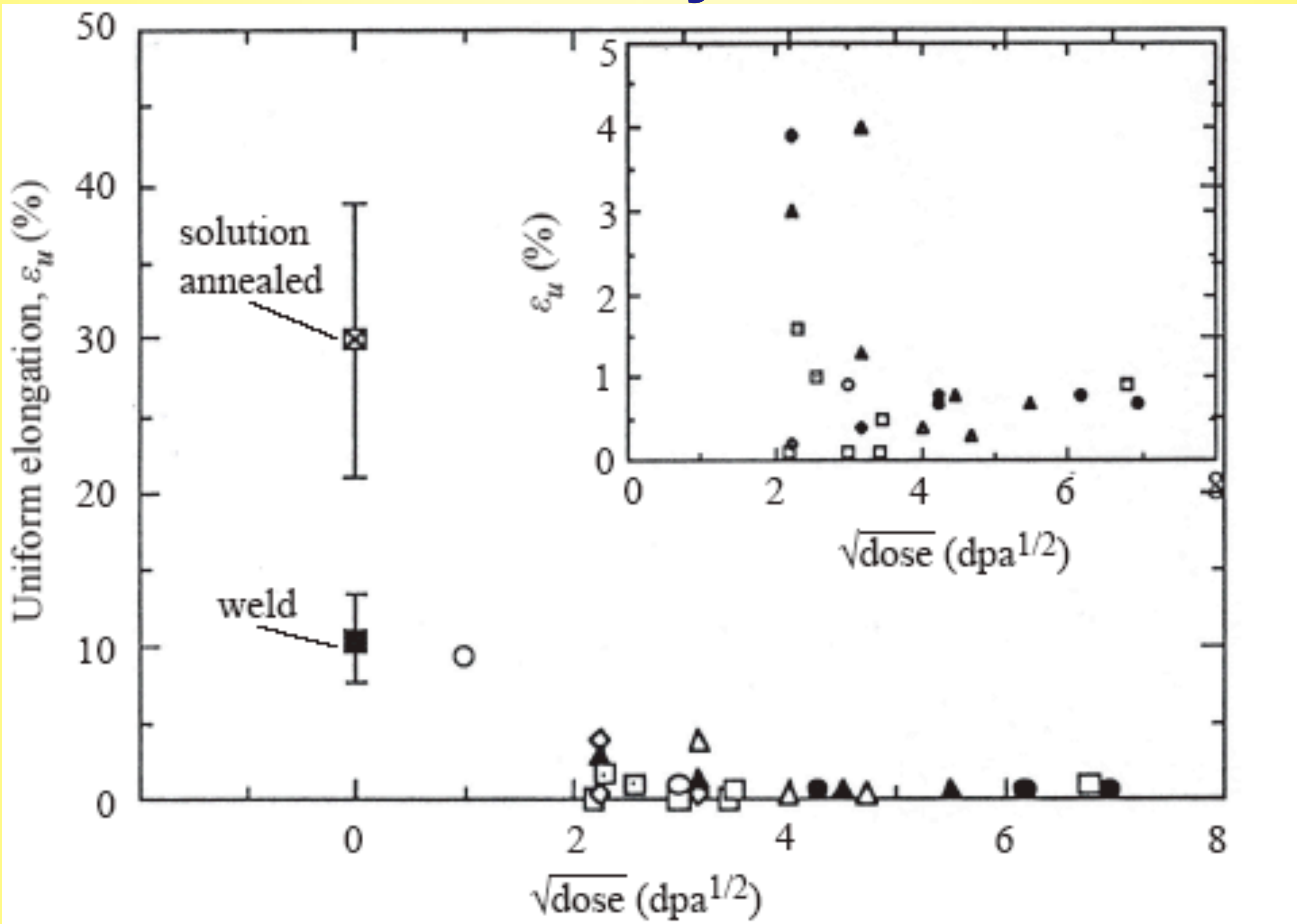
- **This hardening is also observed in many different materials.**
- **Increases in YS and UTS are commonly observed.**
- **Irradiation also results in a drop in ductility.**

Irradiation hardening is widely studied in stainless steels



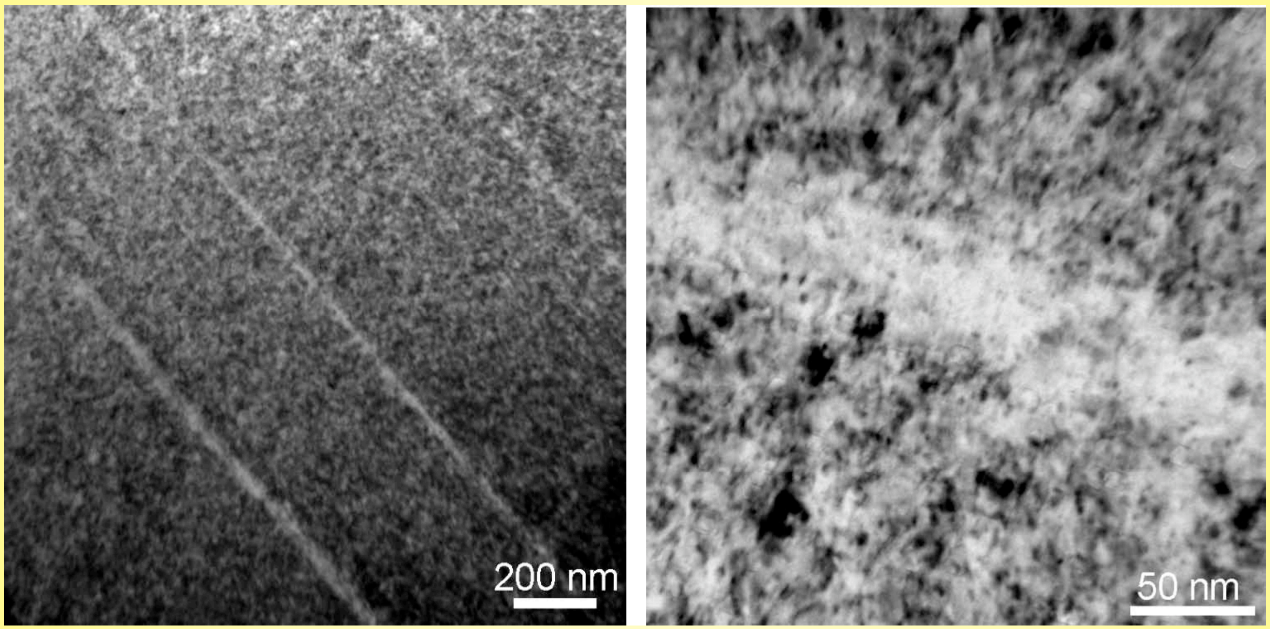
G.S. Was et al, 2007

Hardening also results in a loss of ductility



GR Odette, GE Lucas, JNM, 1991

Irradiation results in localized deformation, which is responsible for loss of strain hardening

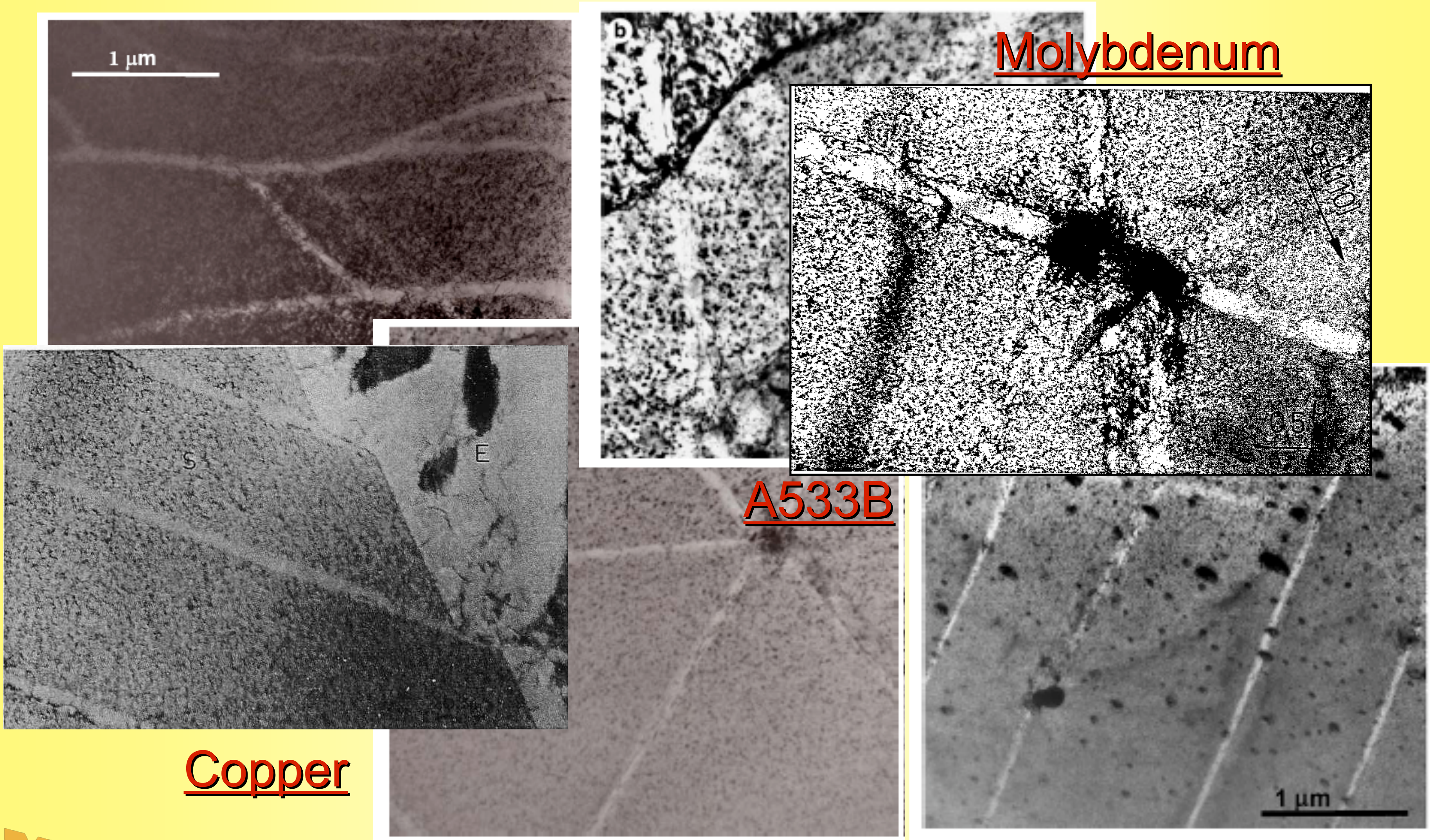


Transmission electron micrographs of dislocation channels in Fe-18Cr-12Ni irradiated to 5.5 dpa at 360°C with 3 MeV protons and strained to 7% at 288°C.

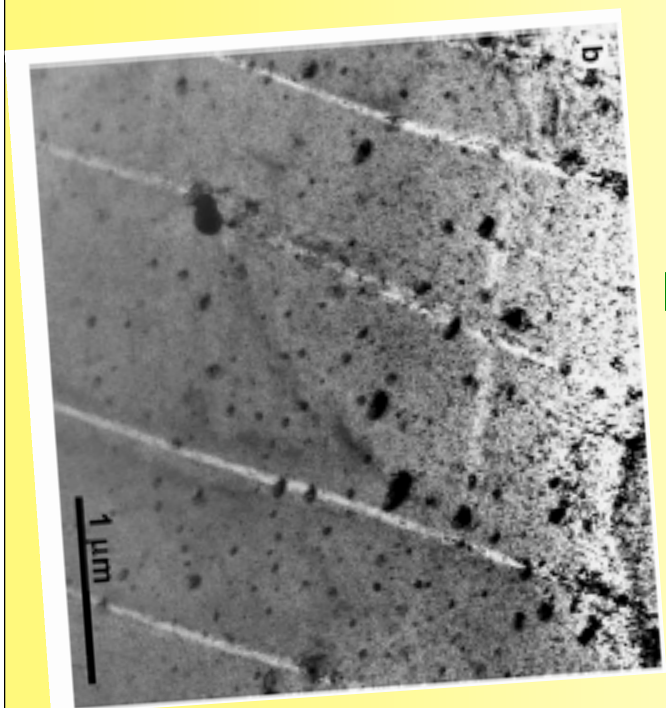
Dislocation channels are visible on the surface of the sample

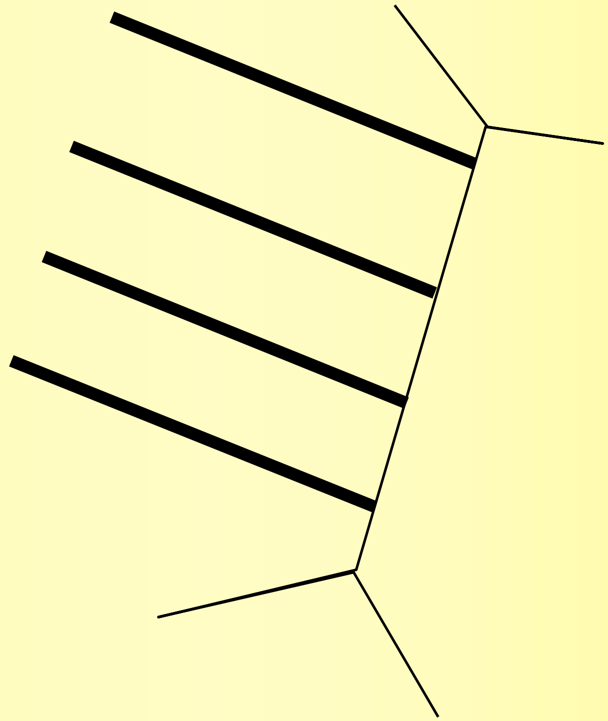
Scanning electron micrograph of dislocation channels intersecting the surface of austenitic stainless steels irradiated to 5.5 dpa with 3.2 MeV protons at 360°C followed by straining to 7% plastic strain at 288°C in argon at 3 x 10^{-7} s .

Localized Deformation Occurs In Many Irradiated Material Systems



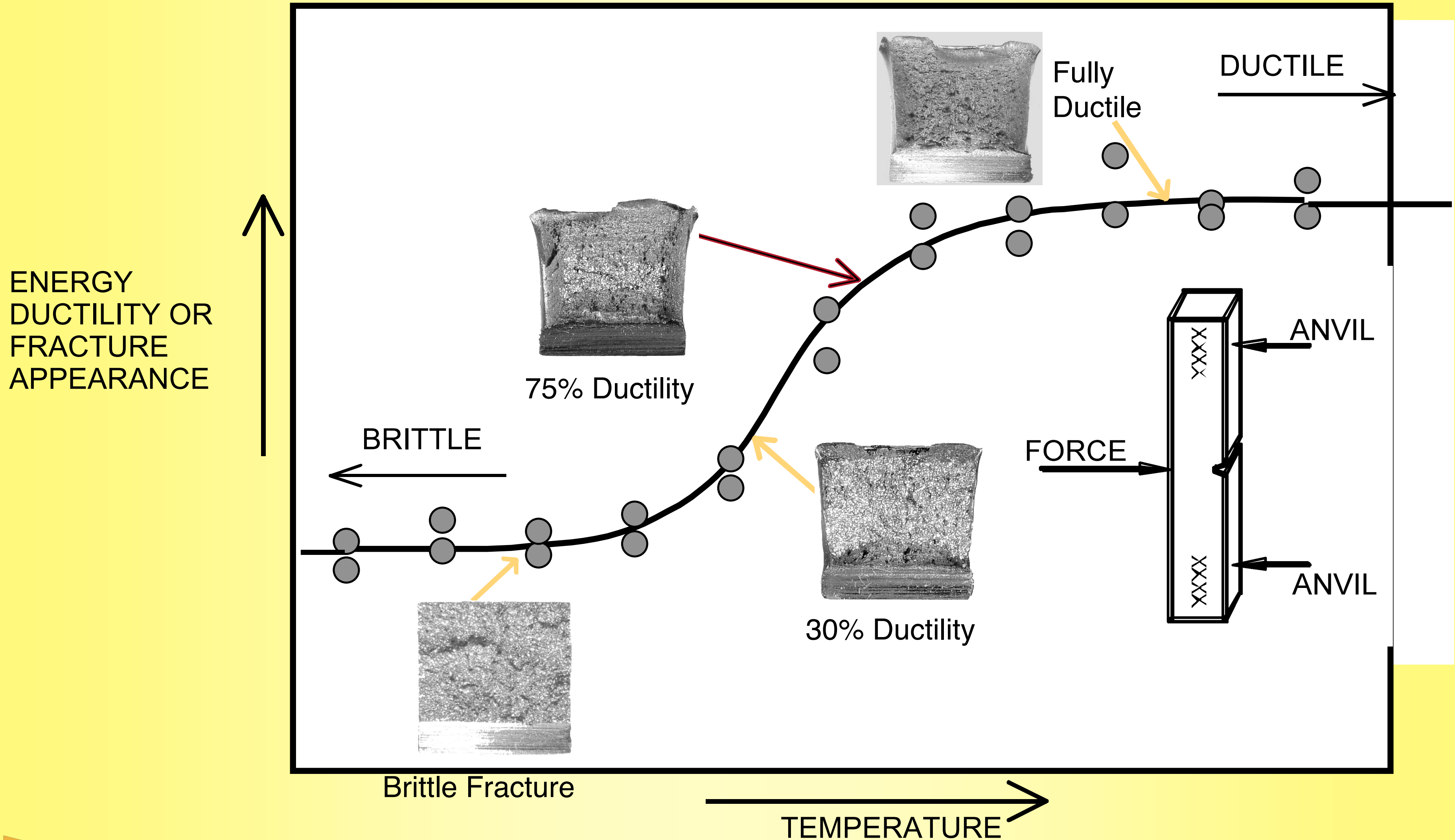
Localized deformation can lead to non-uniform deformation and embrittlement



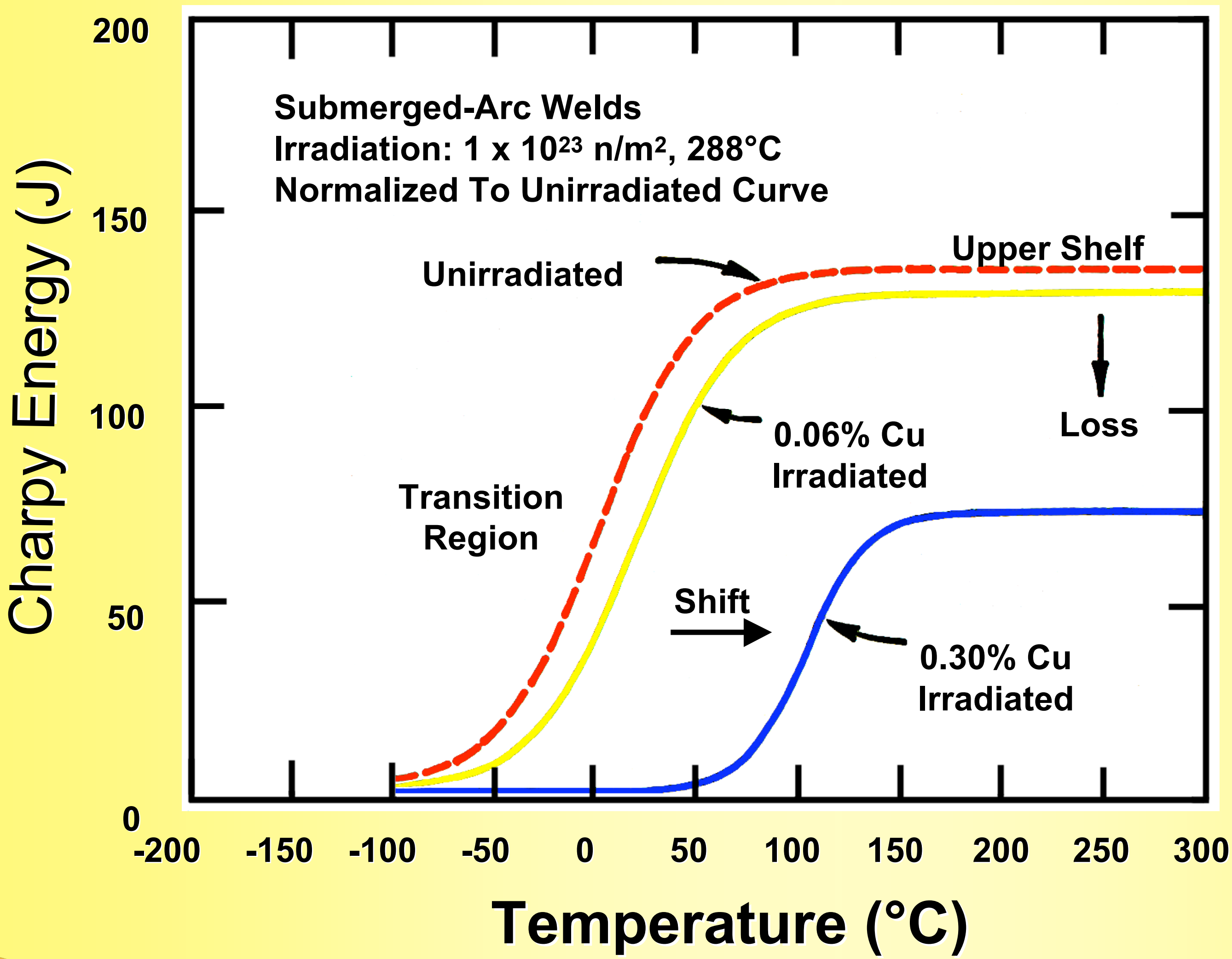


•In channeling, strain becomes concentrated to a few isolated locations.
•Strain within the bands may be several hundred percent!
•If strain cannot be transferred to neighboring grain, it must be accomodated at the boundary.

Loss of ductility can lead to loss of toughness or even brittle failure in some alloys



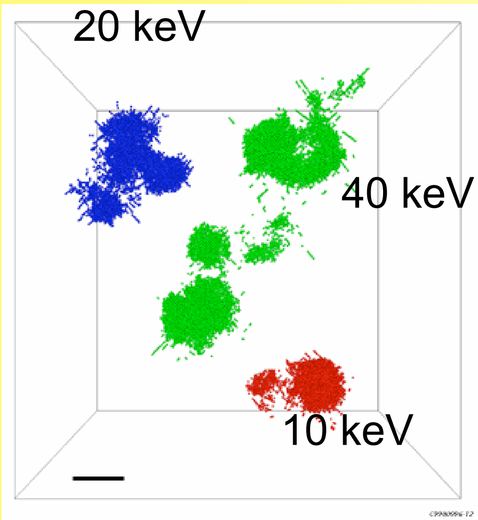
Radiation-embrittlement and the DBTT are a key concern in RPV steels



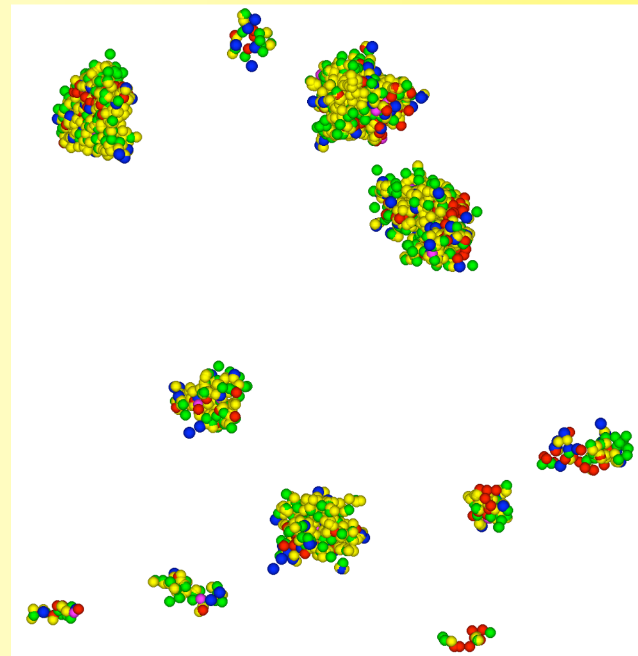
Irradiation Causes Ductile/Brittle Transition Temperature Shift and Upper Shelf Energy Loss — Copper Increases The Effect

T.R. Allen

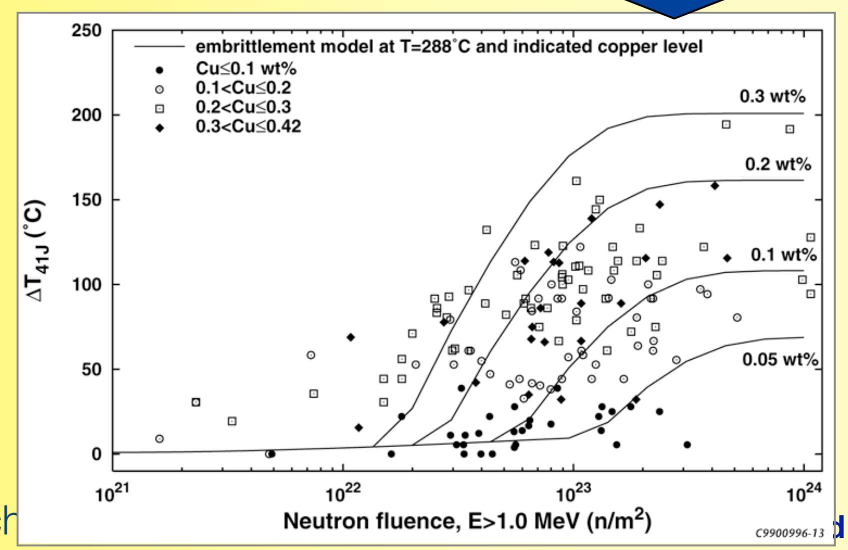
Microstructural Investigations Such As Atom Probe Tomography Are Used to Reveal Mechanisms of Irradiation Embrittlement



Neutron radiation produces an extremely high number density of nanoscale copper-, manganese-, nickel-, silicon-, and phosphorus-enriched precipitates.

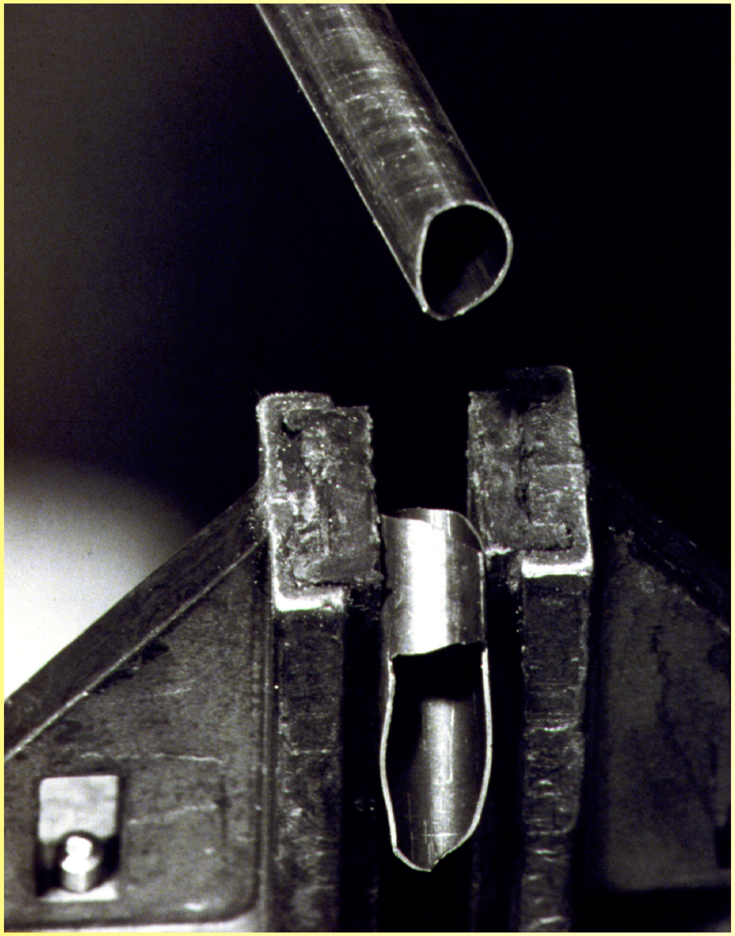


Fe Cu Ni Mn Si P atoms



Combination of experimental, modeling, and microstructural studies leads to advances in predictive capability.

Severe void-induced embrittlement



- 14% swelling
- Failure occurred during clamping in a vise at room temperature.
- Tearing modulus has fallen to zero, with no resistance to crack propagation.
- 316 stainless steel irradiated at ~400ºC
- Embrittlement threshold at ≲10% swelling.

T.R. Allen

Transmutation

- Irradiation in a neutron environment can also result in transmutation.
- Transmutation products may influence materials properties.
  - Segregation
  - Precipitation
  - Chemical compatibility!

A number of common transmutation reactions in reactors can influence irradiation performance

- A number of important reactions occur in reactor environments, varying with spectrum and materials

- Most create helium
  - $^{58}Ni + n_f \rightarrow {}^{55}Fe + {}^{4}He$
  - $^{60}Ni + n_f \rightarrow {}^{57}Fe + {}^{4}He$
  - $^{58}Ni + n \rightarrow {}^{59}Ni + \gamma \rightarrow {}^{56}Fe + {}^{4}He$
  - $^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$

- He production is of interest due to implications on embrittlement in fast reactors.

Helium embrittlement for fast reactors

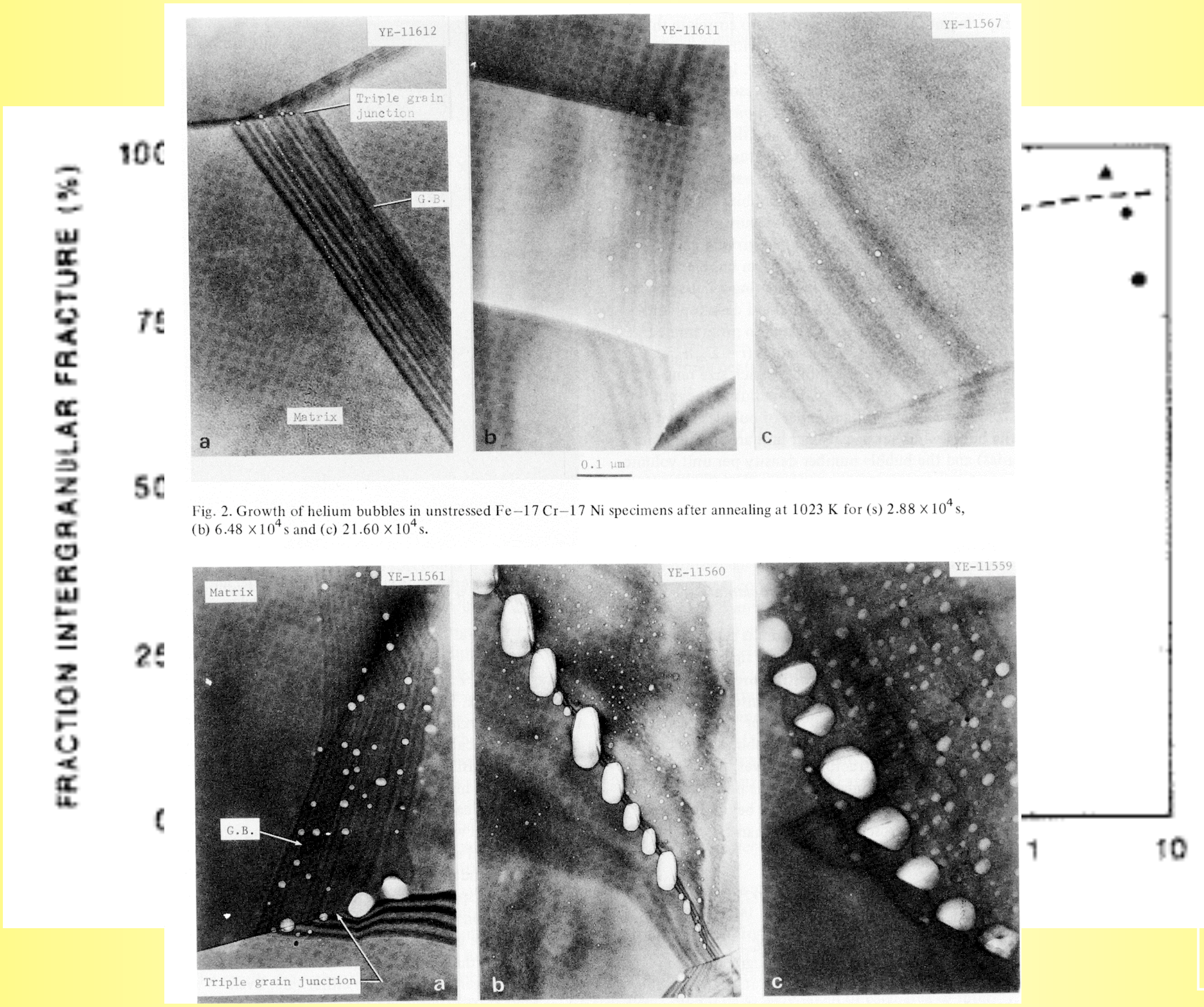


Fig. 2. Growth of helium bubbles in unstressed Fe–17 Cr–17 Ni specimens after annealing at 1023 K for (s) 2.88×10^4 s, (b) 6.48×10^4 s and (c) 21.60×10^4 s.

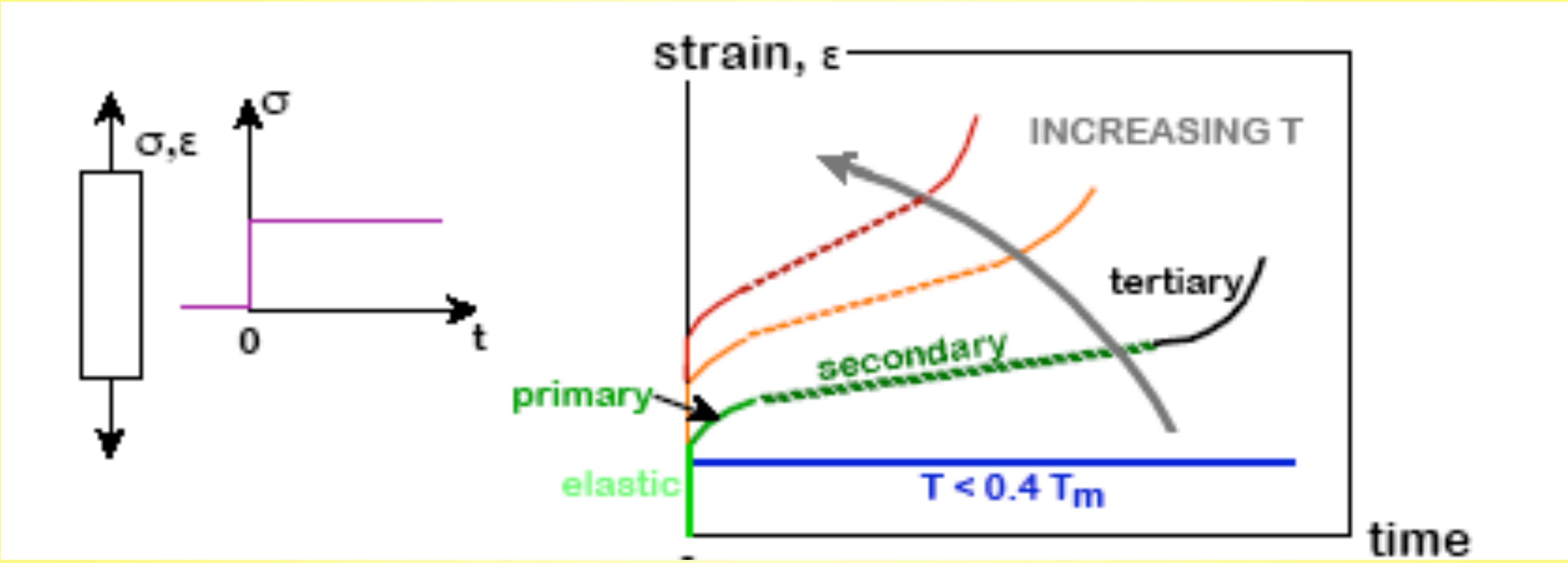
0 MPa

19.6 MPa

van der Schaaf and Marshall, 1983

Embrittlement via Intergranular fracture is dependent on helium content, temperature, and strain rate

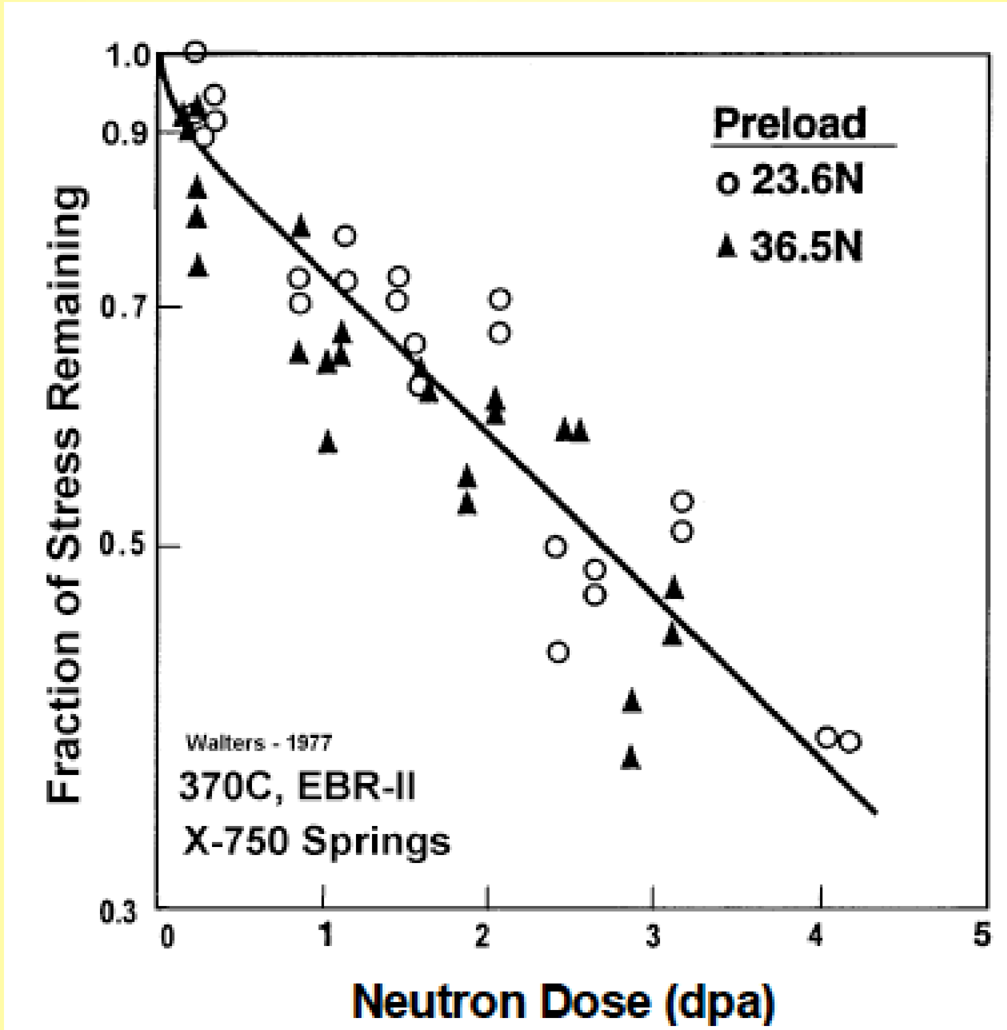
Irradiation induced creep



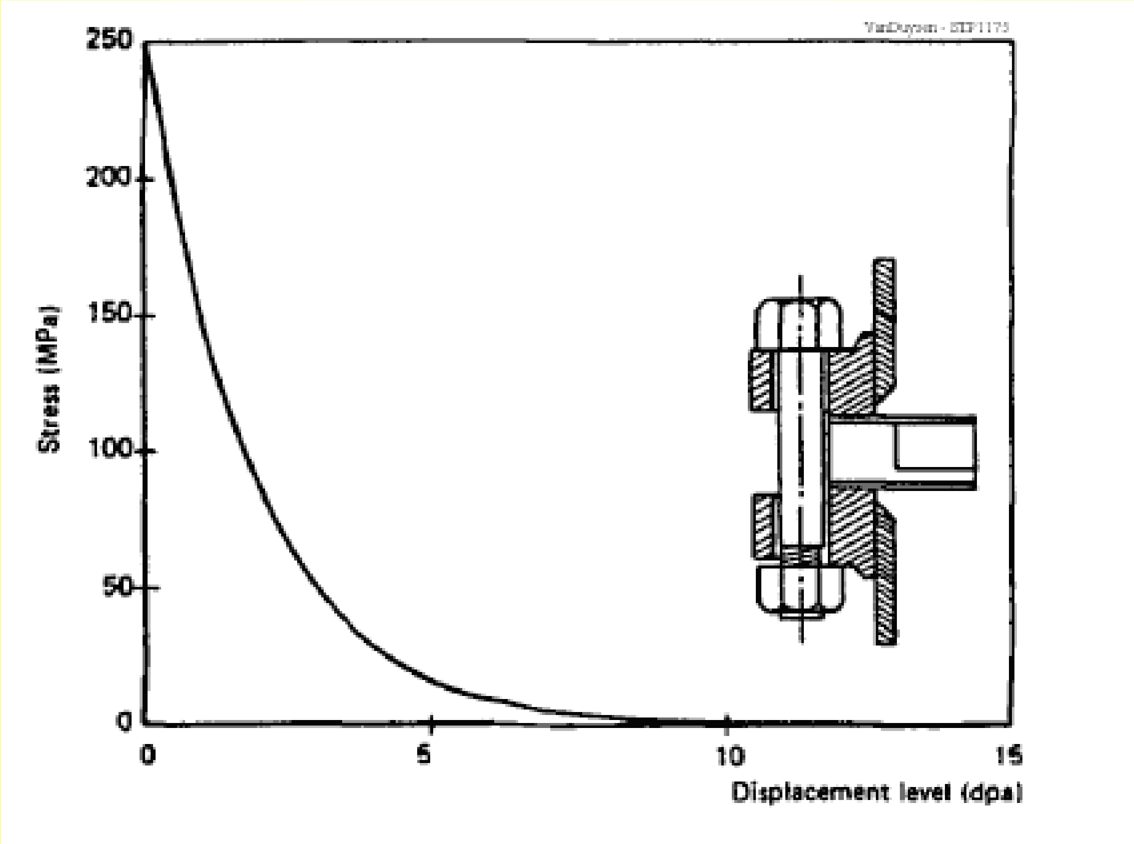
- **Radiation produced point defects increase diffusion and allow creep at lower temperatures**

T.R. Allen

Irradiation induced stress relaxation via creep in X-750 springs at 370°C

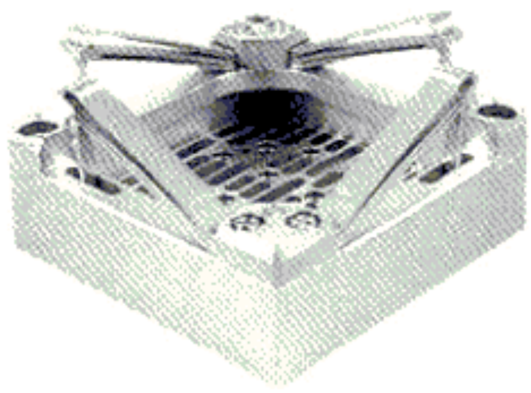


Irradiation induced stress relaxation via creep in stainless steel at 288°C

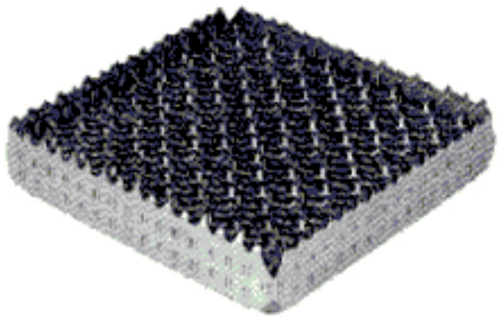


ML Grossbeck, LK Mansur, JNM 1991

Stress-relaxation is an important factor for a number of LWR core internals

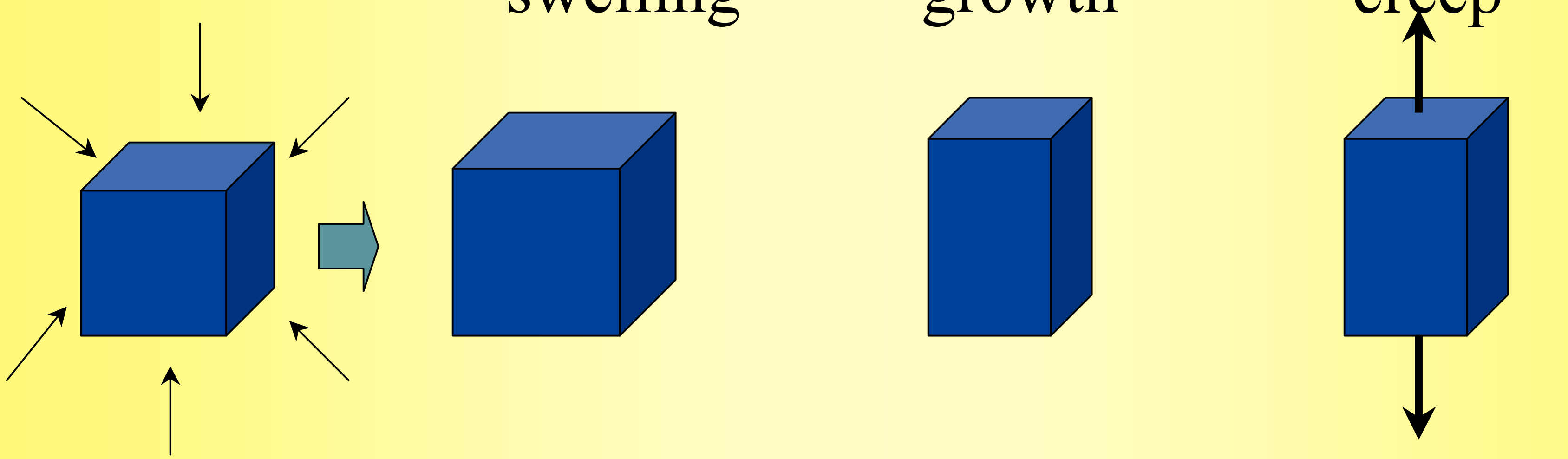


○ Top Nozzle



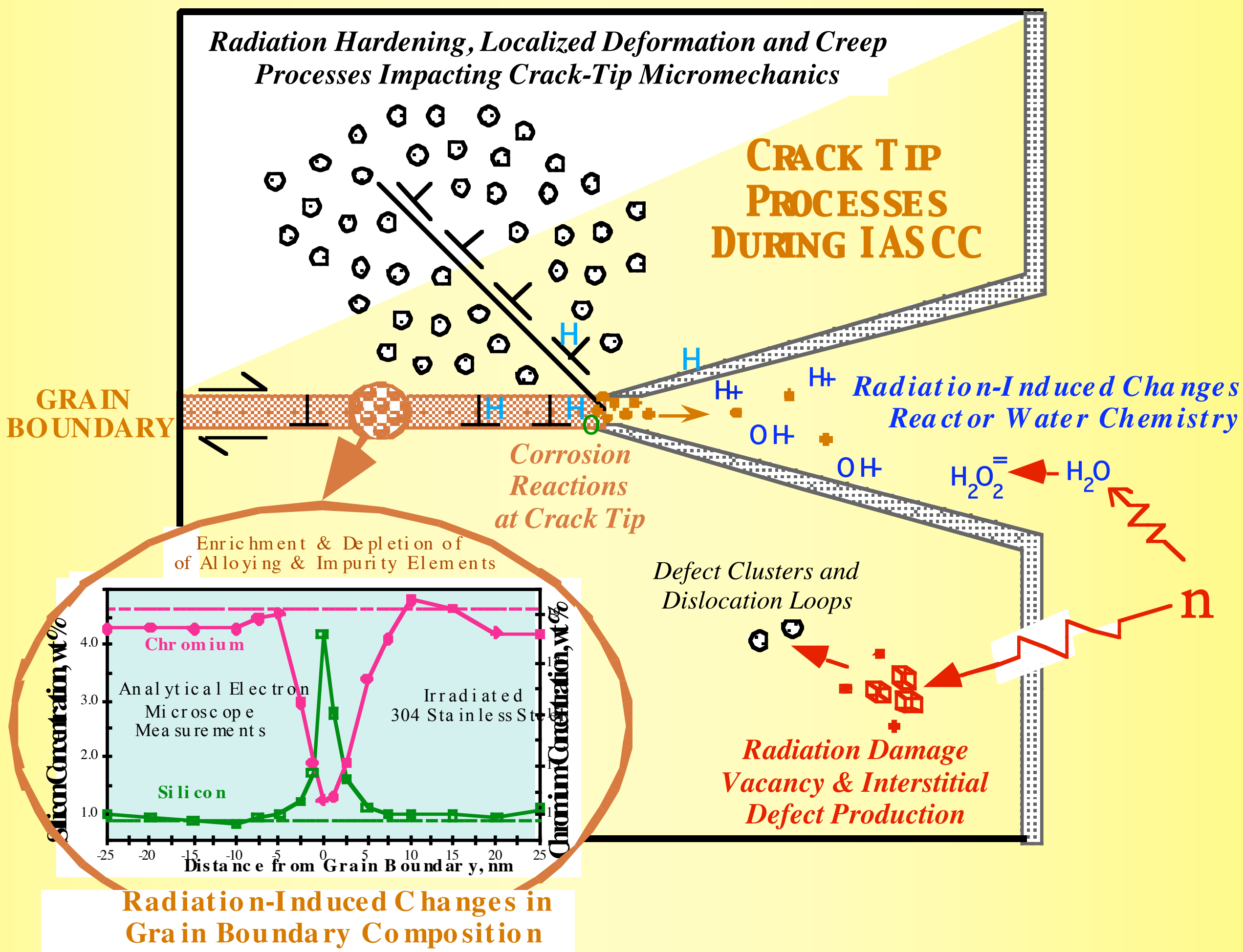
○ Grid Asembly

Dimensional stability is heavily influenced by irradiation



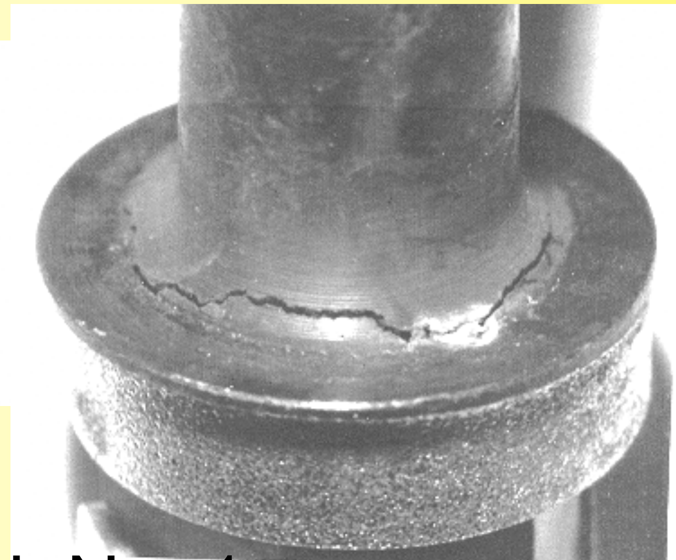
	swelling	growth	creep
	unstressed	unstressed	stressed
	$\Delta V/V > 0$	$\Delta V/V = 0$	$\Delta V/V = 0$
	undistorted	distorted	distorted

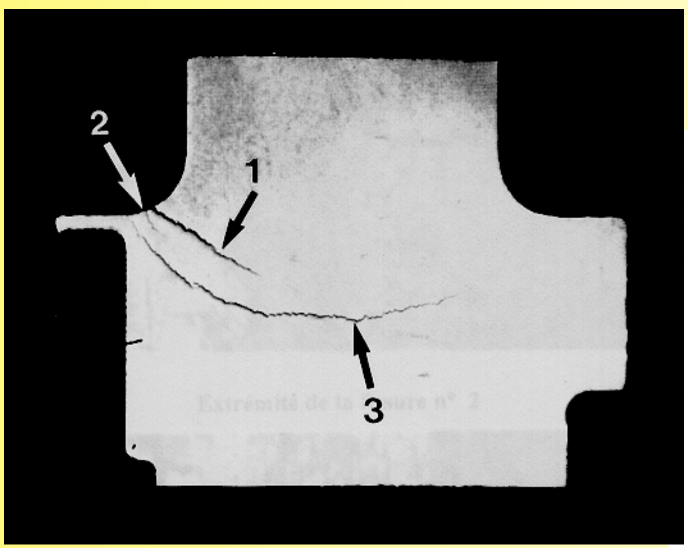
Irradiation also influences corrosion processes

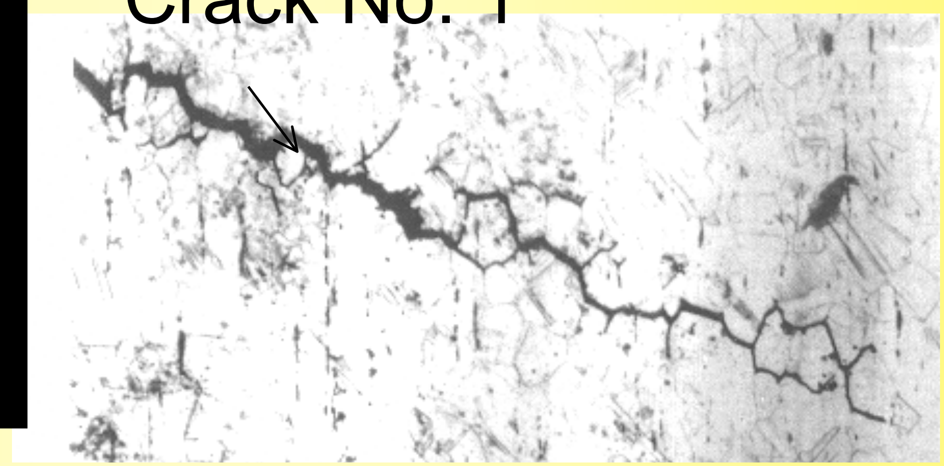


S. Bruemmer and E. Simonen, Corrosion 50 (1994) 940.

Irradiation Assisted Stress Corrosion Cracking (IASCC) in PWRs

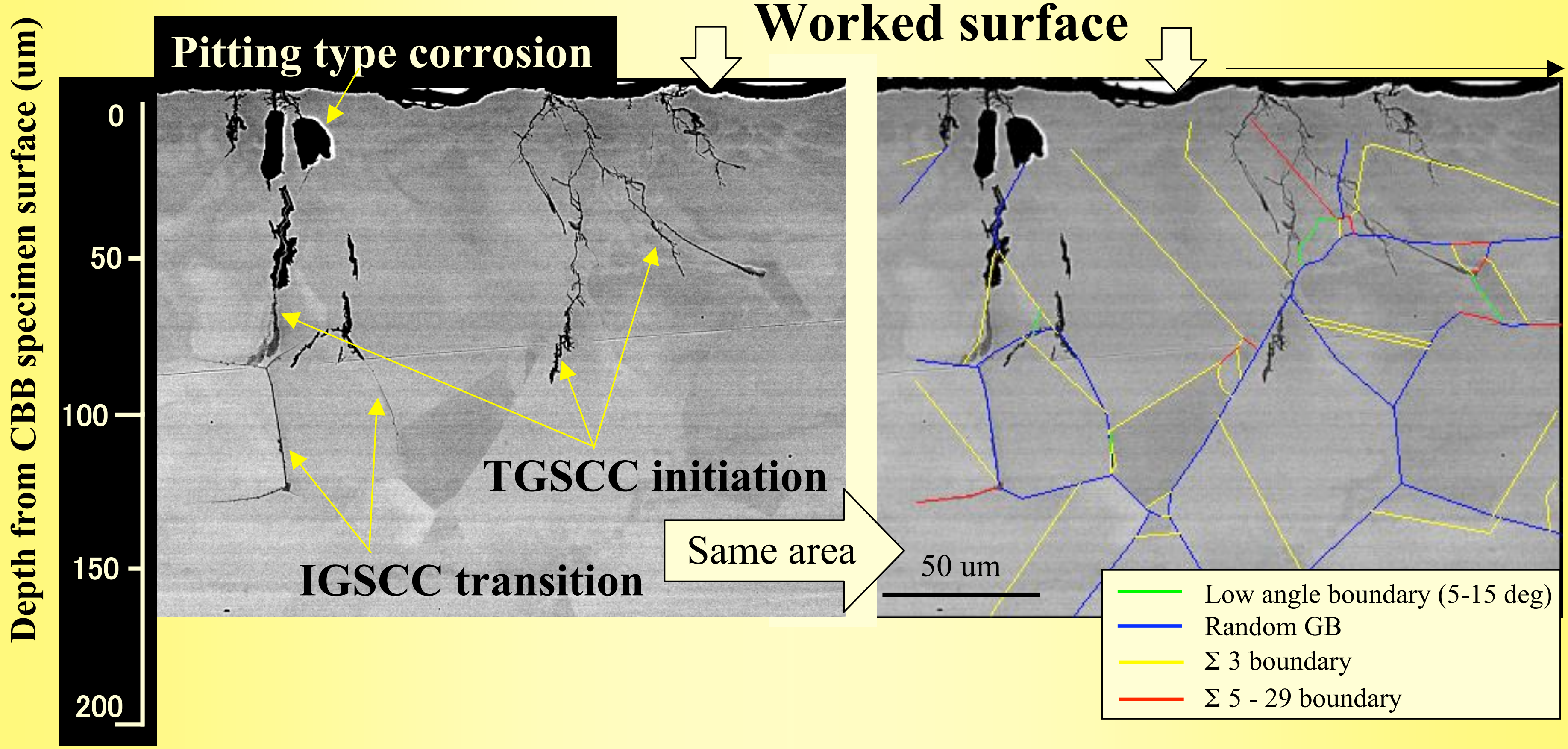






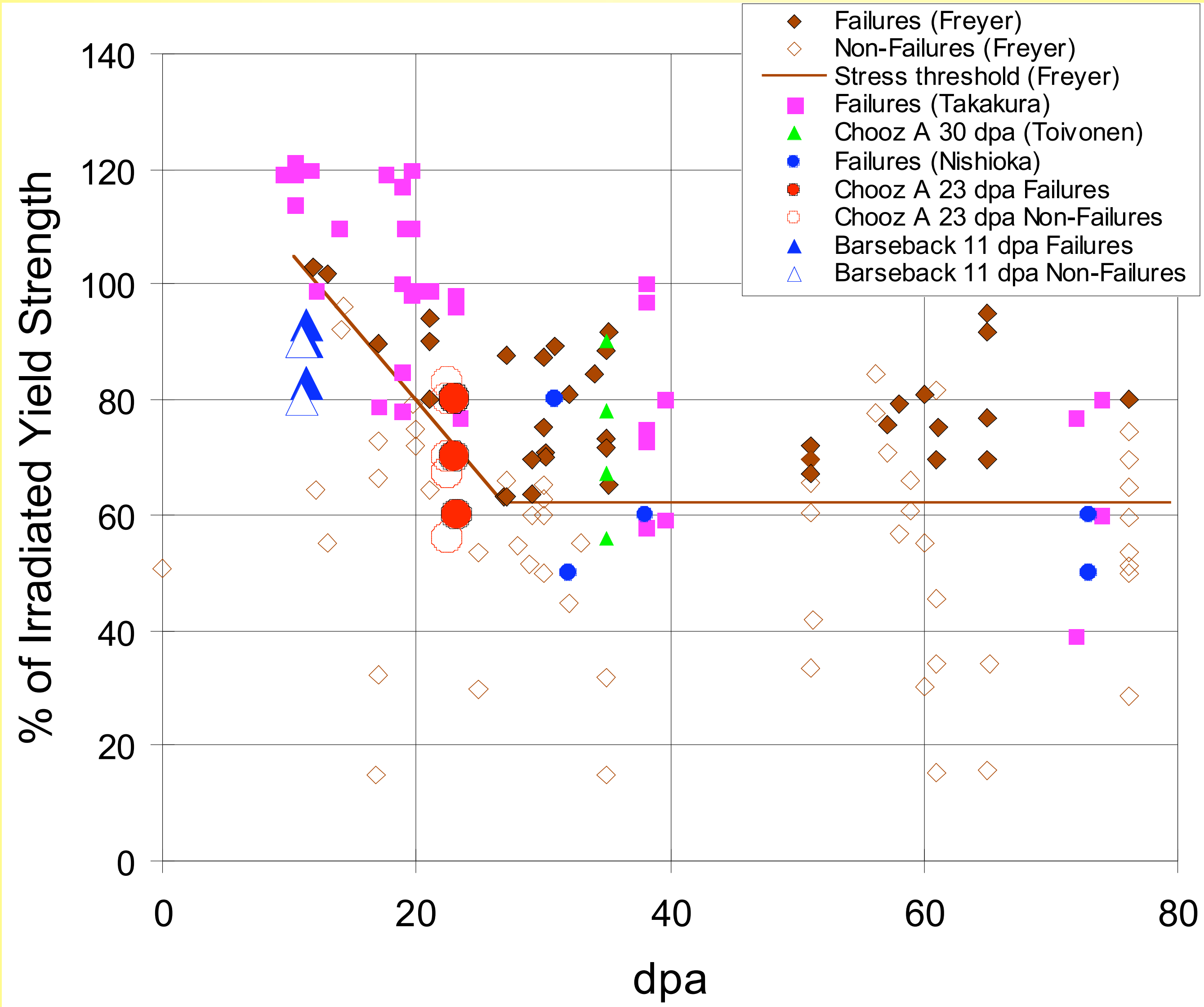
Source: P. Scott

IASCC in BWRs



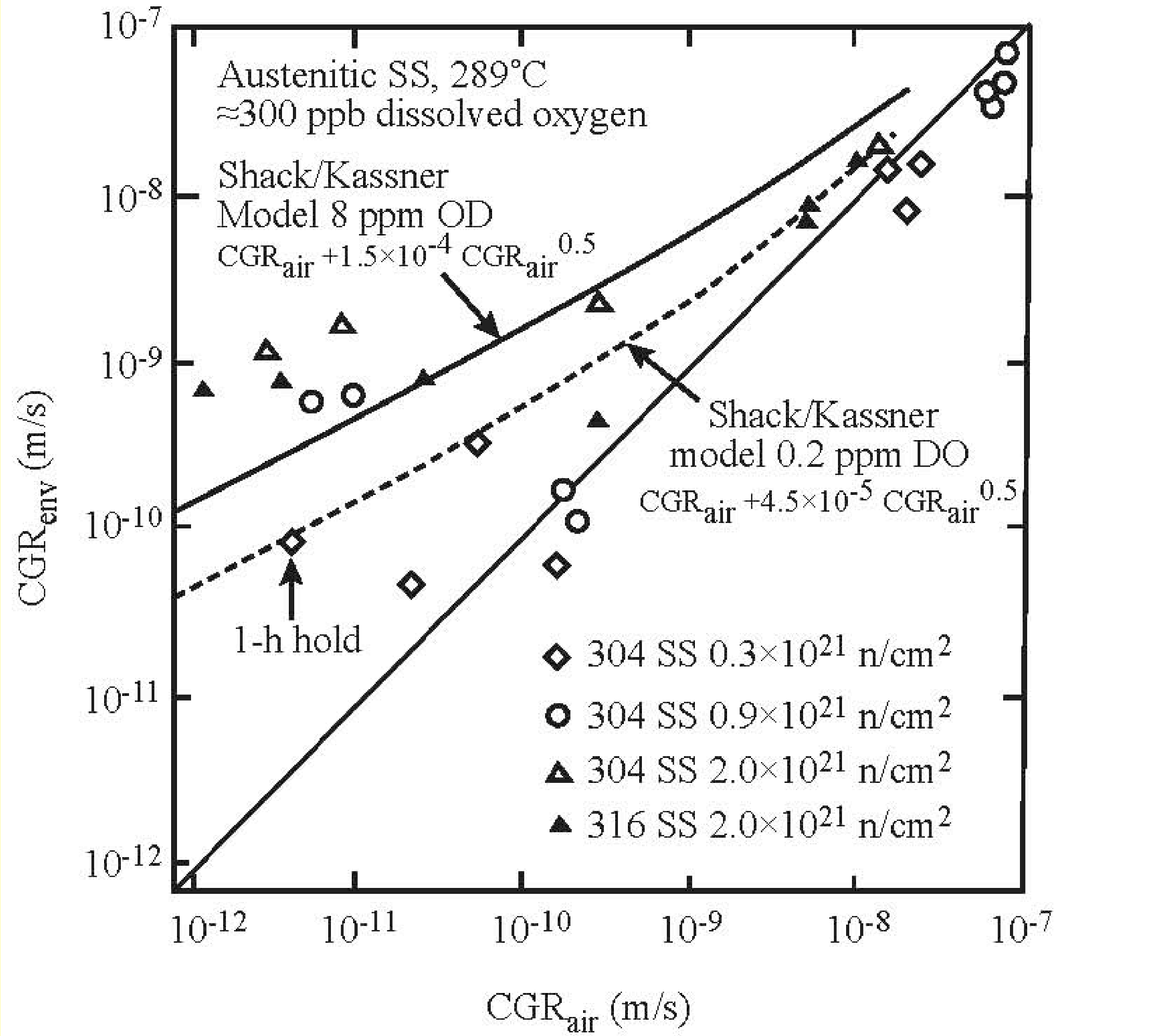
- TGSCC was typically initiated from worked surface and was propagated in deformation area.
- Transition from TGSCC to IGSCC was observed in deeper area.
- Pitting type corrosion was occasionally observed associating with TGSCC.

Failure as a percent of irradiated yield strength vs. dose



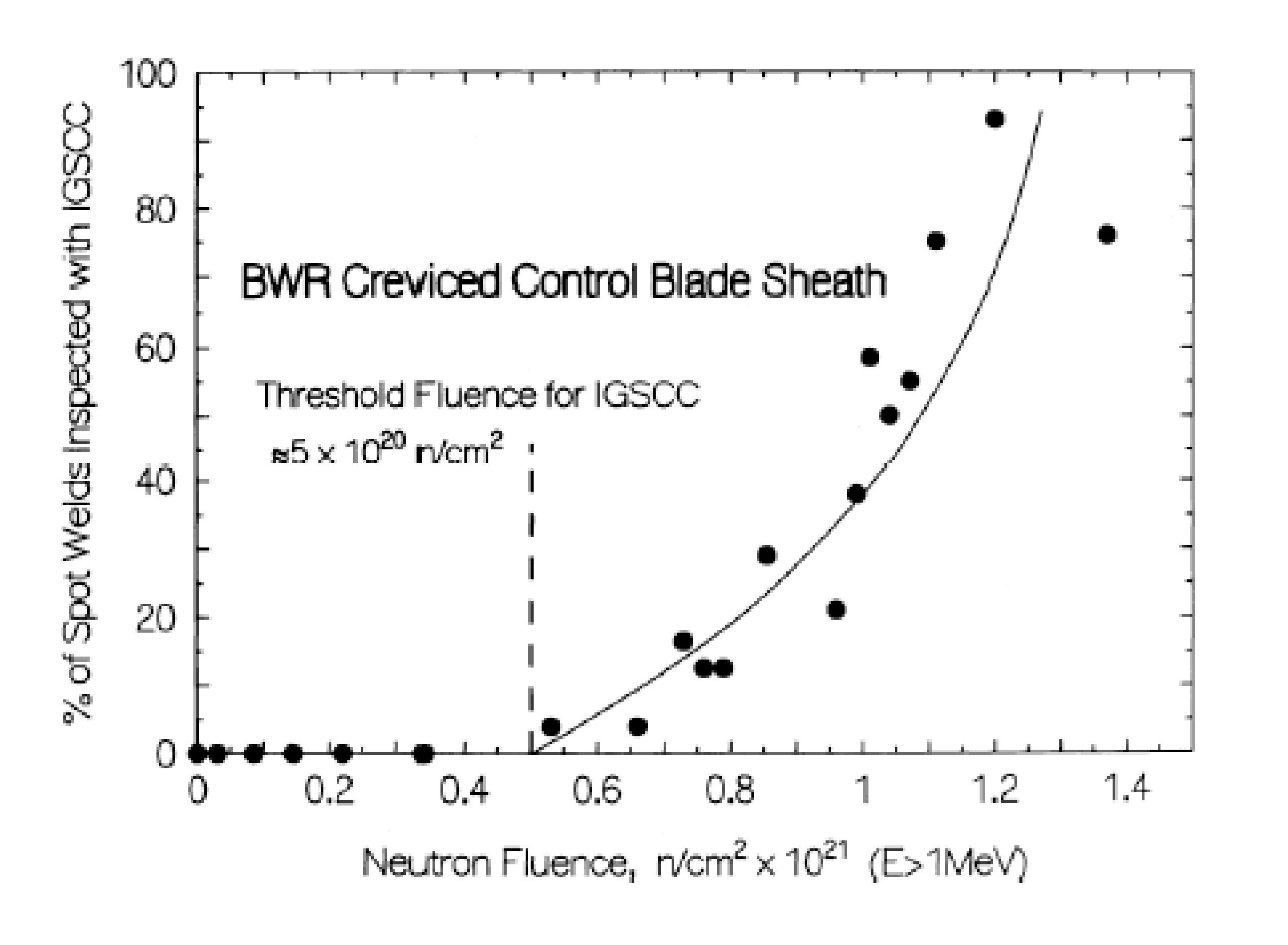
CIR final report, 2010

Influence of irradiation on crack growth rate in austenitic stainless steel tested in 288°C water



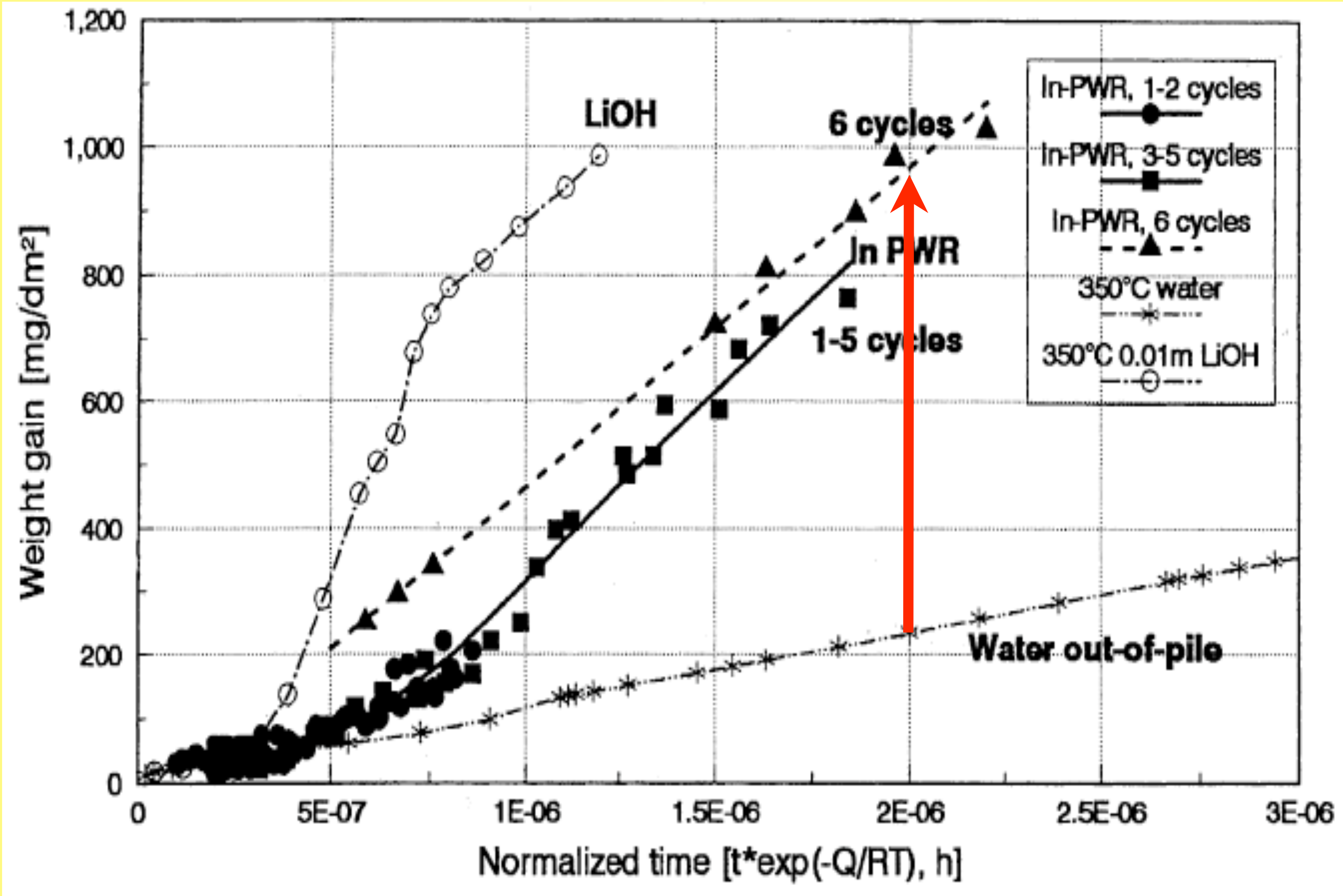
OK Chopra et al., 2003

Dependence of IASCC on neutron fluence for creviced control blade sheaths in BWRs



Source: PL Andresen

Irradiation-enhanced oxidation in zirconium alloys



B. Cox JNM 2005

Summary

- All effects of irradiation damage stem from the formation and diffusion of excess vacancies and interstitials.
- The interactions between these vacancies and interstitials determine the dominant form of irradiation-induced degradation.
- The appearance and magnitude of the effect depends on parameters such as temperature, dose, dose rate, alloy condition, alloy, stress and stress state.
- Physical effects effects of irradiation are RIS, swelling, growth, precipitation, dislocation loop formation and growth,
- Mechanical effects - hardening, embrittlement, creep - require imposition of the a stress.
- Additional effects occur due to interaction with corrosion.

Thanks to the following for allowing me to use their slides!

- Jeremy Busby
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- Randy Nanstad
- Steve Zinkle
- Everett Bloom
- Steve Bruemmer
- Frank Garner
- Roger Stoller
- Lance Snead